W&C 21 July 2000

Results from DONUT*:

First Direct Evidence of ν_τ

The primary goal is to directly observe the charged-current interactions of the tau-neutrino.

The experiment locates and identifies tau-lepton decays using an emulsion target and spectrometer.

Byron Lundberg FERMILAB
for the DONUT *collaboration*

*D*irect *O*bservation *of* Nu T*au*

W&C 21 July 2000

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Outline

OVERVIEW of EXPERIMENT

Digression 1: Brief Review of n_t

NEUTRINO BEAM

The INTERACTION sample of 203 EVENTS

Digression 2: Modern Emulsion Primer

DECAY SEARCH

BACKGROUNDS

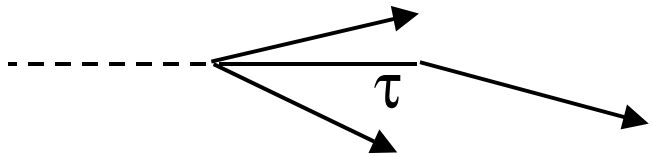
The SIGNAL

CONCLUSION

Essential quantities

Overview

- Use 800 GeV protons $\rightarrow$ beam dump
- Emulsion 36*m* from dump
- Magnetic/passive shield protects emulsion
- ν flux < 0.001 of NuTeV
- Search for ν_τ interaction by topology: *kinks*



Digression 1: The ν_τ Story

1975 - τ lepton discovered ; ν_τ assumed to exist

1980's - CLEO, ARGUS, LEP τ decays: nothing unusual

1986 - E531 : no direct couplings to $\nu_{e\,,\,\mu}$

1991 - LEP demonstrates 3.00 ν's

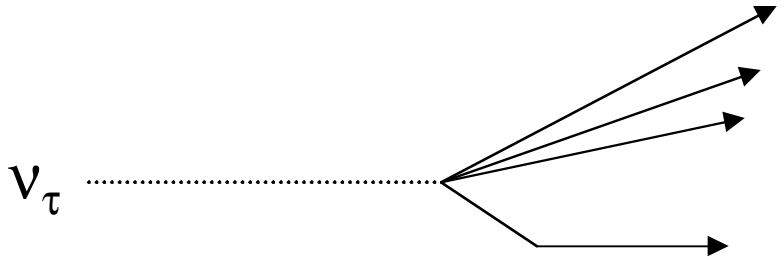
1998 - Evidence of ν osc. $\nu_\mu \leftrightarrow \nu_\tau$

ν_τ Properties

- the usual SM numbers
- mass $< 16\ \mathrm{MeV}/c^2$ (direct)
- dipole moments: $\mu_{\nu\tau} < 4.2\times10^{-7}\ \mu_B$ (preliminary)

τ Decays

- Topological BR $\tau \rightarrow$ one charged particle: 86%
- $\tau \rightarrow e\ \nu\nu$ 18%
- $\tau \rightarrow \mu\ \nu\nu$ 18%

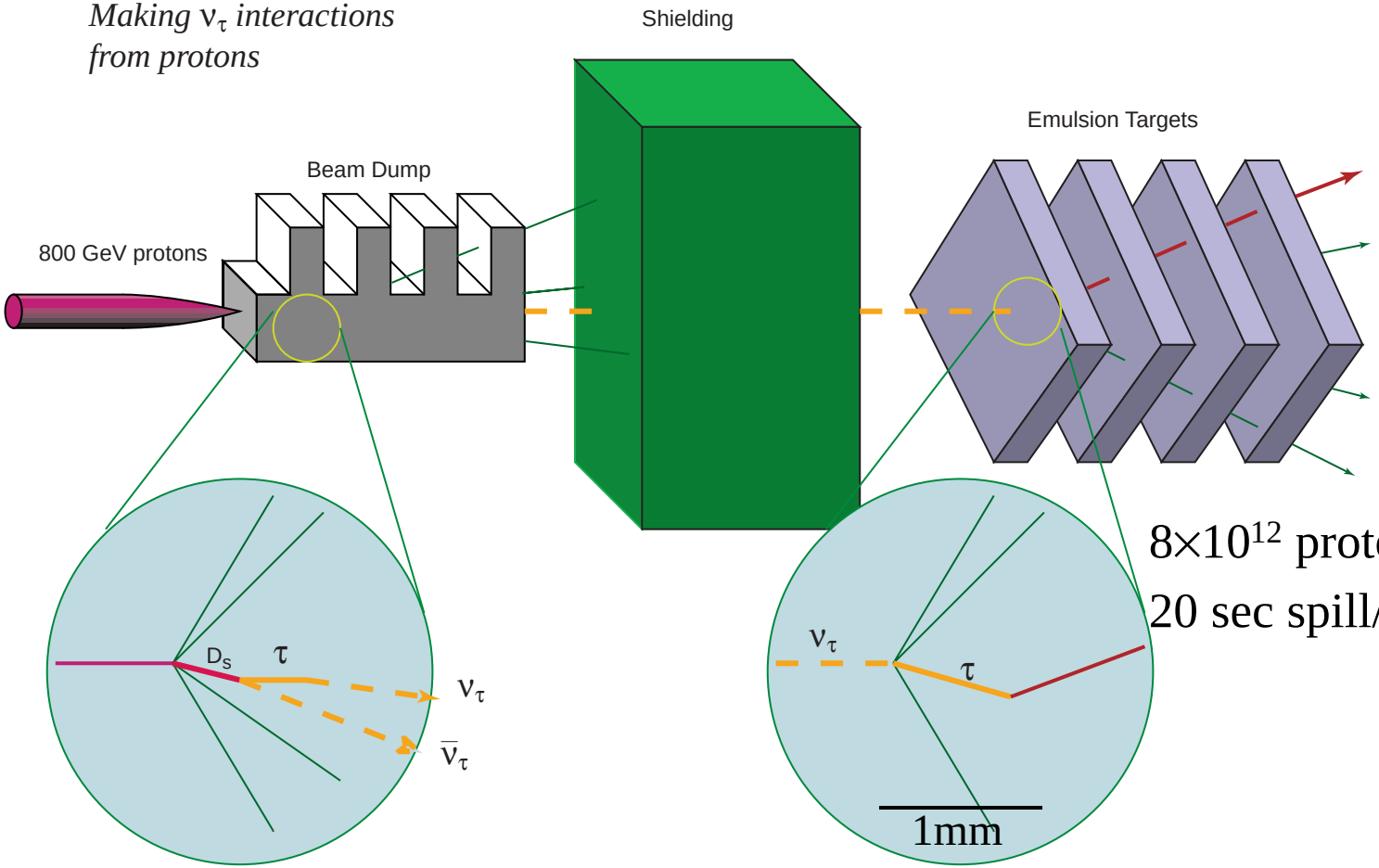


- $c\tau_\tau = 87\ \mu m \Rightarrow$ 2.3mm *mean decay length in DONUT*

Prompt Neutrino Beam

E-872

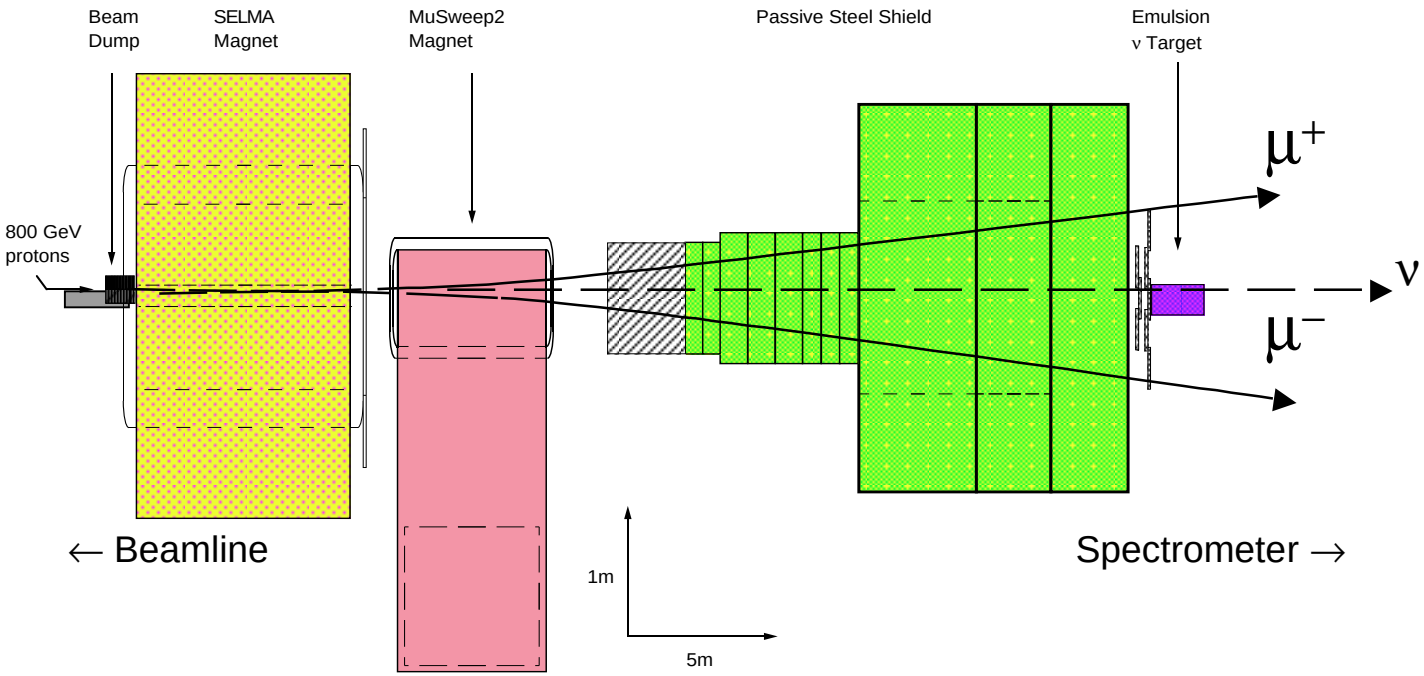
Making ν_τ interactions from protons



8×10^{12} protons/ spill

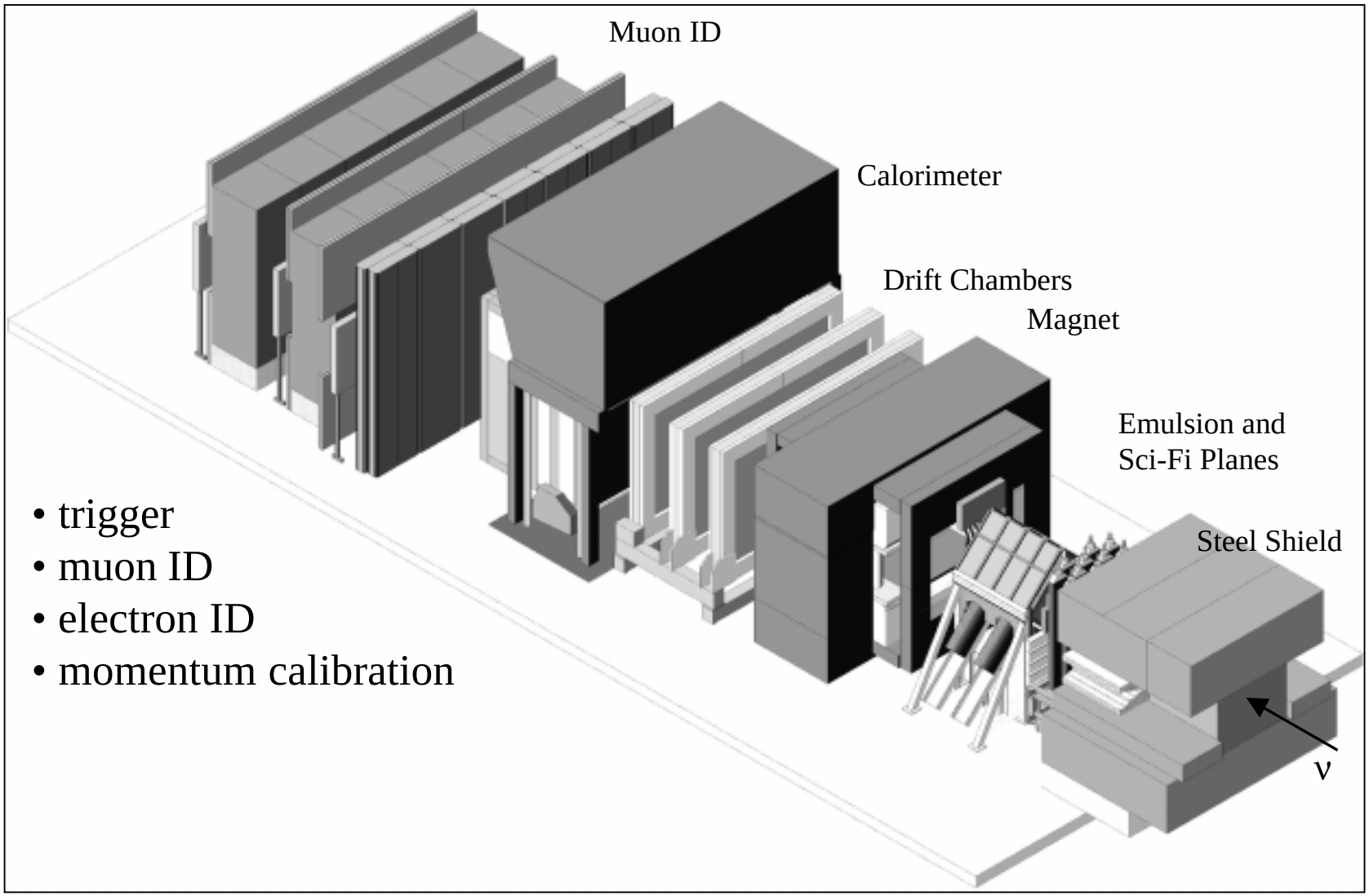
20 sec spill/ minute

Prompt ν Beam /Shield



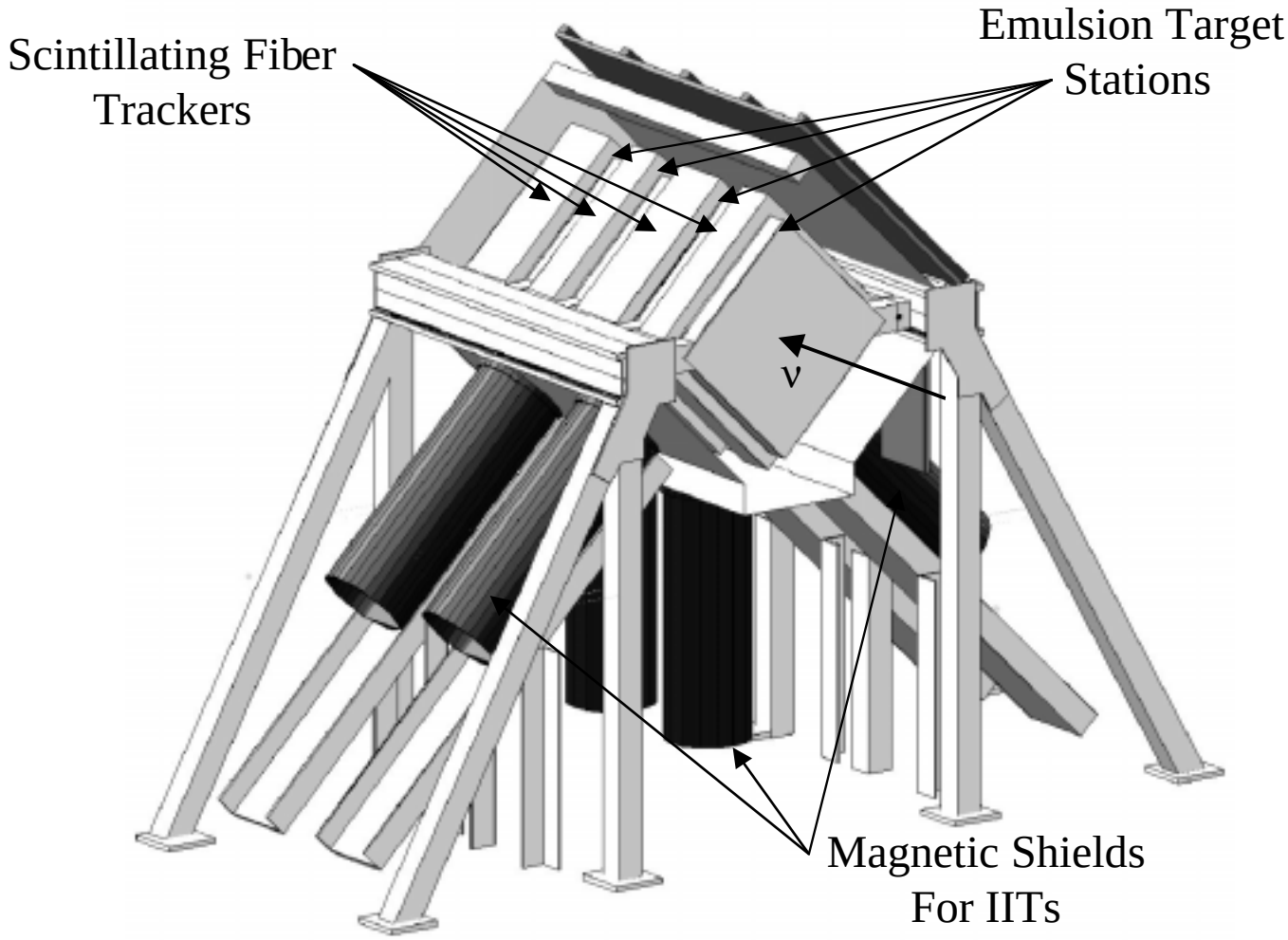
- Emulsion Target 36m from beam dump
- Muon rate ~ 2×10^4 per 10^{13} *pot* in target area

Spectrometer

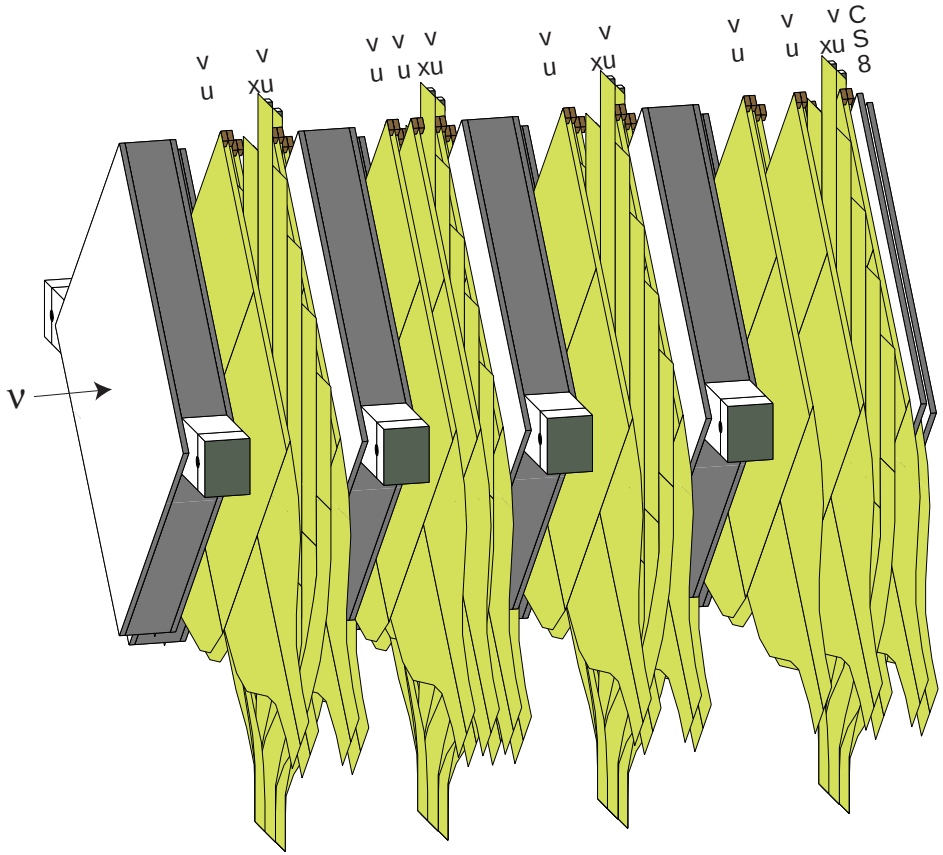


- trigger
- muon ID
- electron ID
- momentum calibration

Emulsion Target



Emulsion Target / Vertex Detector



- Four target stations
- 260 kg total mass
- Interleaved with sci-fi
- Fibers → vtx prediction
- Total 7 modules exposed
- Modules ~2-3 X_0 each
- ~ 0.2 - 0.3 λ_{int} each

Installation of Emulsion Module

April 1997

ν Flux / Interactions

Prompt ν beam $\Rightarrow$ number $\nu_e \sim$ number ν_μ

Primary ν_τ source $D_S \rightarrow \nu_\tau \tau \rightarrow \bar{\nu}_\tau X$

$\nu_e + \nu_\mu$	2.5×10^{-4} /(*pot* m^2)	52 GeV
ν_τ	2.1×10^{-5} /(*pot* m^2)	54 GeV

Total *protons on target* = 3.6×10^{17}

Calculated number of interactions = 1100 (ν_μ, ν_e, ν_τ)

Data taken from April to September 1997

ν_τ Sources

- 1. Primary Source: $D^+_S \to \nu\,\tau^+ \to X\,\bar{\nu}$

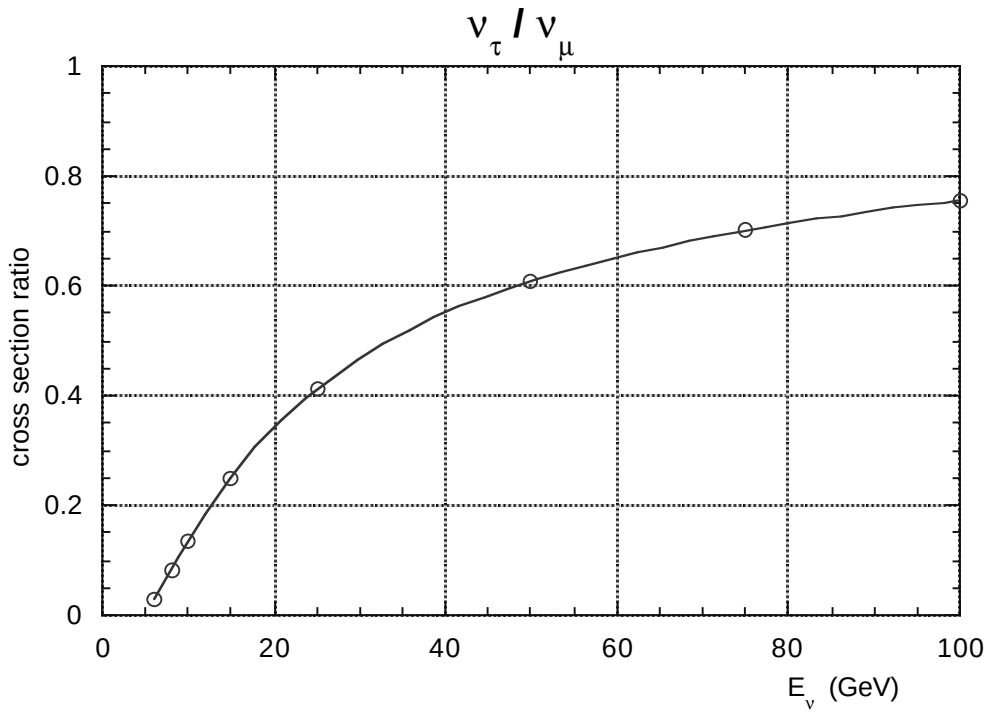
$$BR(D_S^{\pm} \to \tau^{\pm}\nu_\tau) = \left(\frac{G_F^2}{8\pi}\tau_{D_S}\, m_{D_S}\right) \cdot f_{D_S}^2 \left|V_{cs}\right|^2 m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{D_S}^2}\right)^2 \quad = 6.1 \pm 1.0\%$$

- 2. $D^+ \to \nu\,\tau^+ \to X\nu$ (rate 5% of D_S)

- 3. D_S from secondary interactions in dump (rate 8% of D_S)

- 4. $B \to \tau\, X$ (rate 1.3% of D_S)

How many ν_τ?



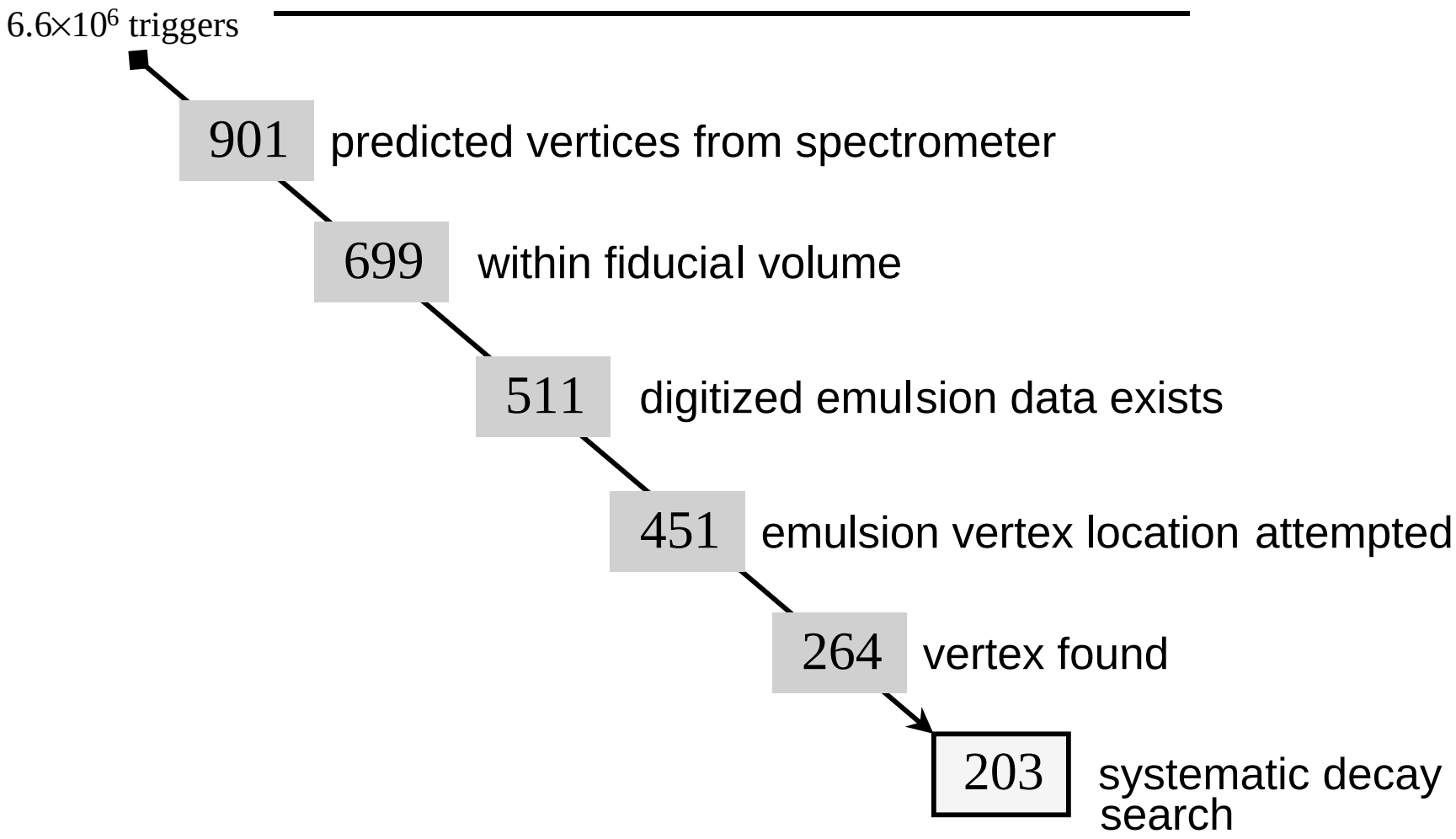
Expected number of ν_τ interactions:

4.8% of total

Uncertainties:

D_S production	±20%
$f_{Ds} \Rightarrow$ BR	±15%

Data Set

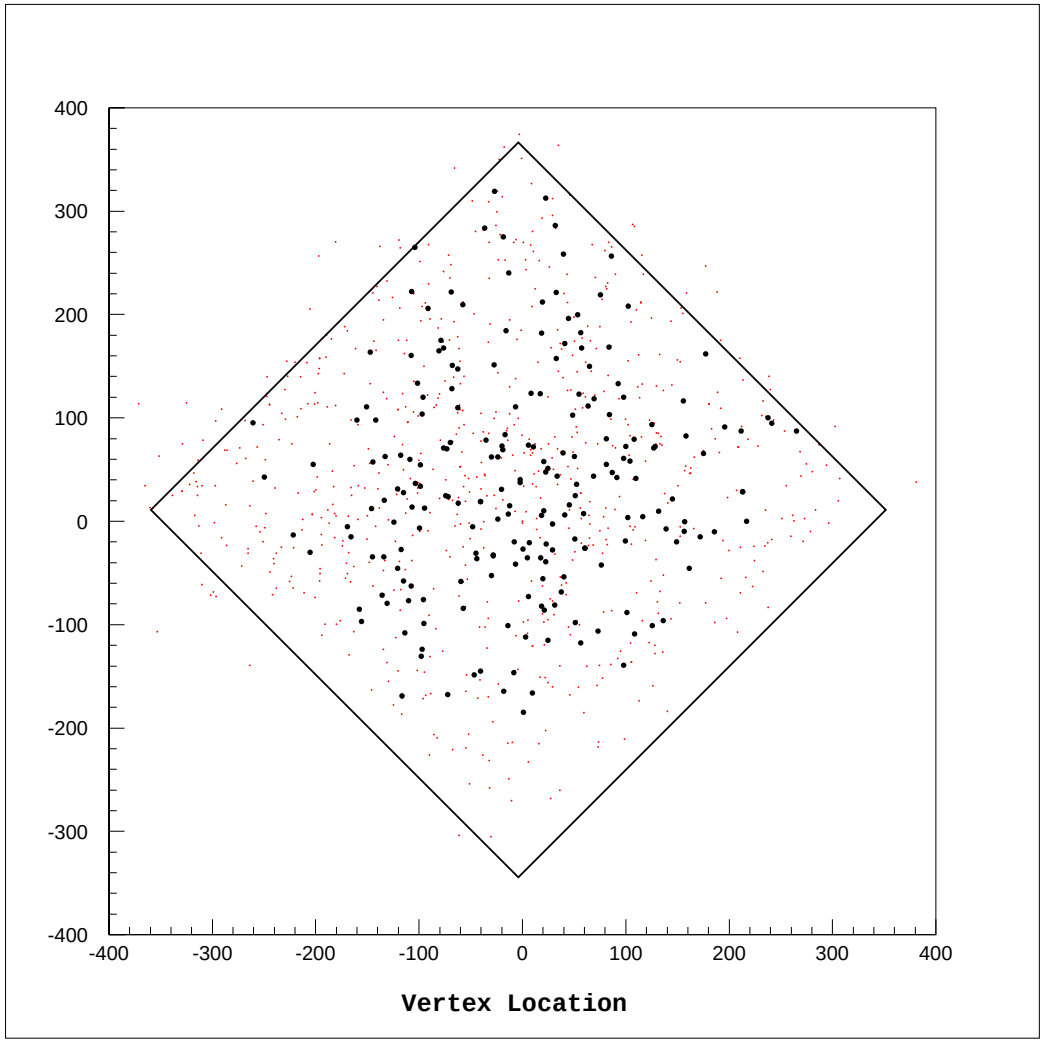

6.6×10^6 triggers
901
predicted vertices from spectrometer
699
within fiducial volume
511
digitized emulsion data exists
451
emulsion vertex location attempted
264
vertex found
203
systematic decay search

Data Sample : 203 events

203 events:

- Primary located in emulsion
- Emulsion data well calibrated
- Decay search performed
- Systematic studies *nearly* complete

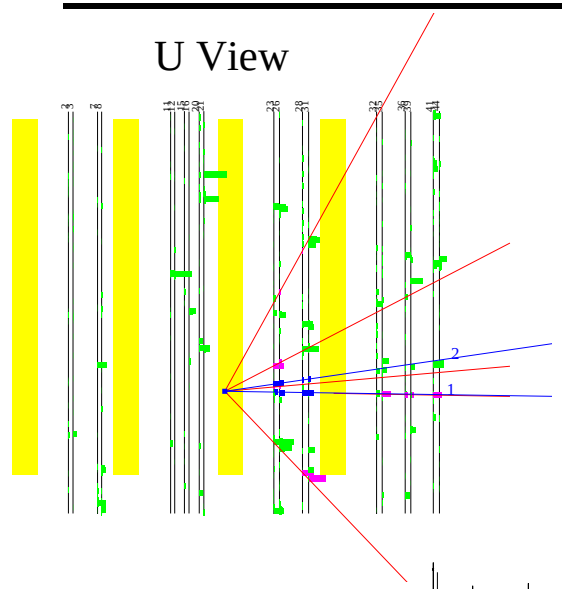
Interaction Vertex Distribution

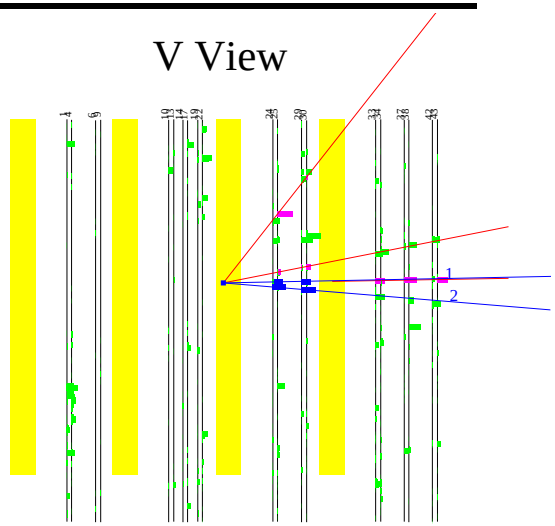


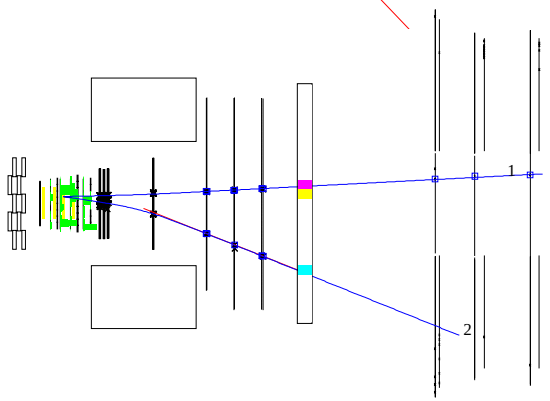
Predicted interaction vertices projected in *x* - *y* plane

Black dots : 203 set
Red dots : 901 predictions

ν_μ CC interaction







DONUT

Fermilab E-872

Run= 3232 Event= 3434

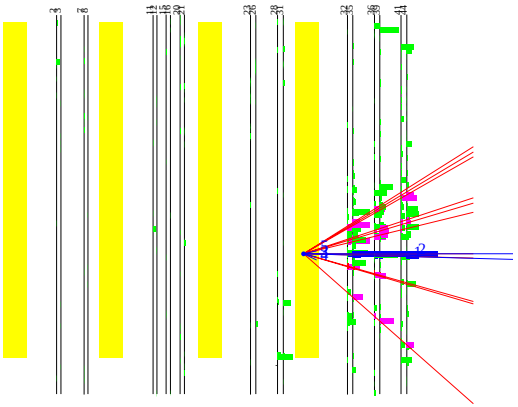
Muon CC

Station 3

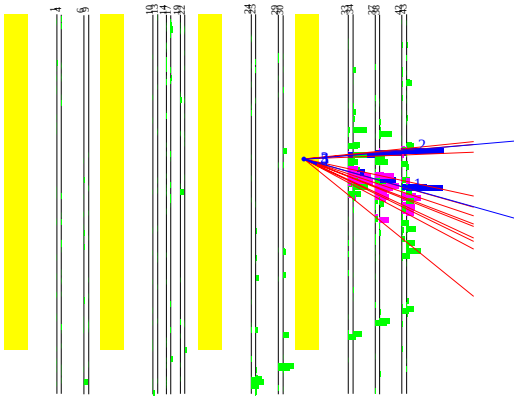
ECC800 Emulsion

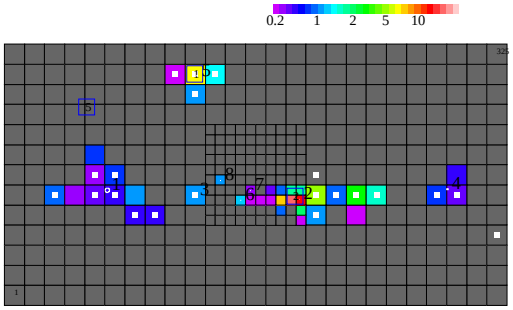
ν_e CC interaction

U View



V View





1	4.7
2	82.1
3	0.8
4	1.3
5	10.8
6	1.0
7	0.3

Cluster Σ E 104 GeV

DONUT

Fermilab E-872

Run= 3250 Event= 470

Electron CC

Station 4

Bulk Emulsion

203 set : ν_μ CC Events

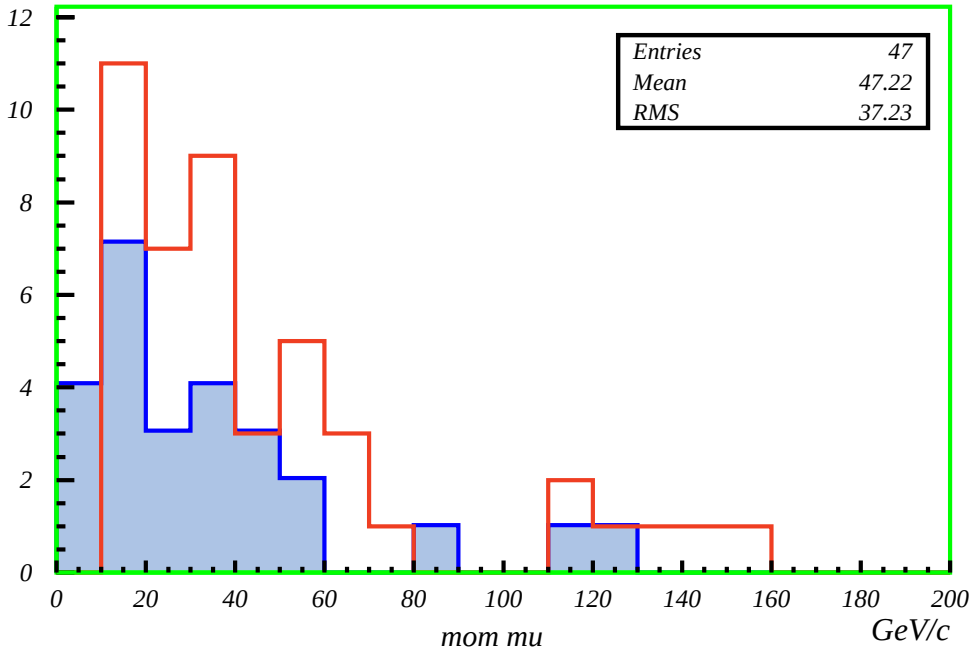
75 ν_μ CC interactions with μ ID'd

47 μ^-

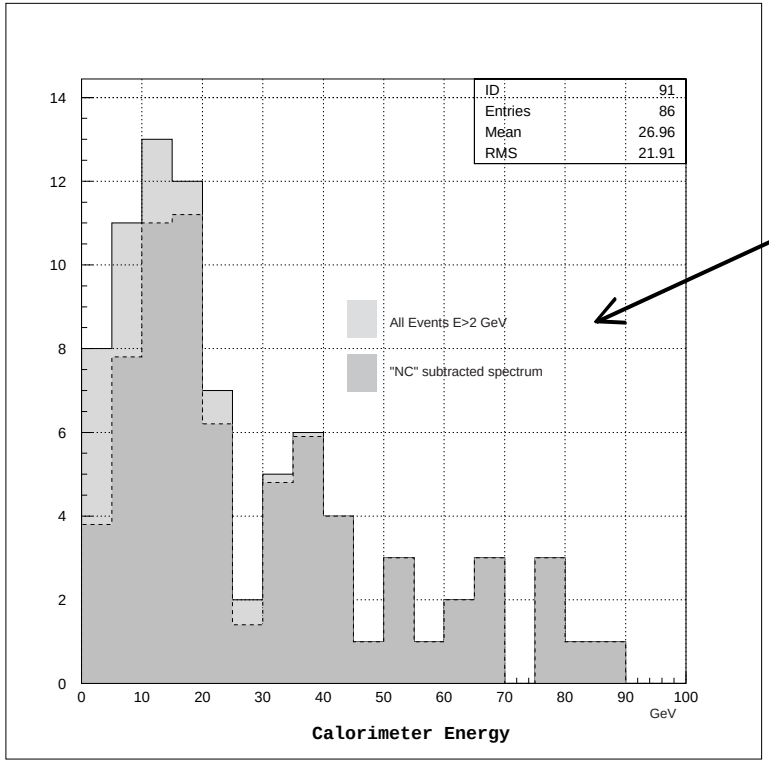
28 μ^+

$$\frac{N(-)}{N(+)} = 1.7$$

expect 1.8



203 set: Composition



86±11 ν_μ CC interactions
(acceptance corrected)

Calorimeter energy spectrum:
79±14 ν_e CC interactions

$\Rightarrow \nu_e \sim \nu_\mu$ in no. interactions

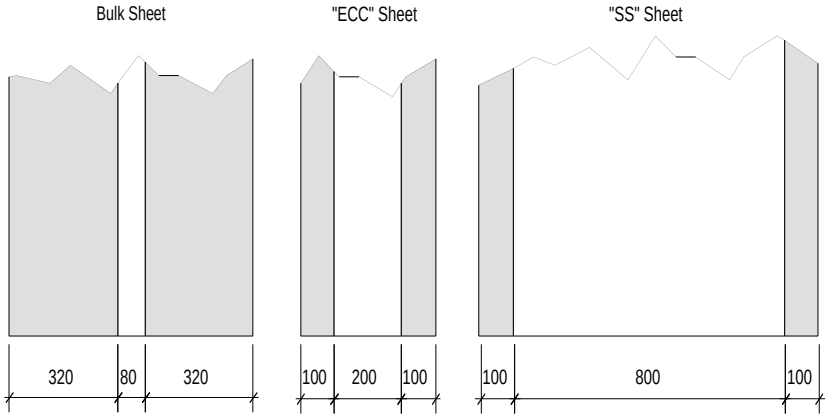
$\Rightarrow \nu_\mu$ non-prompt < 0.3×prompt

Recall ν_τ rate 4.8% ⇒10±3 events

Digression 2: Modern Emulsion

- Target design - ECC type vs bulk type
- Digitized emulsion: Analysis flow
- Scanning stations at Nagoya University
- Performance: efficiency, resolution
- Momentum determination using scattering
  - Essential for τ decay analysis

Emulsion Plates



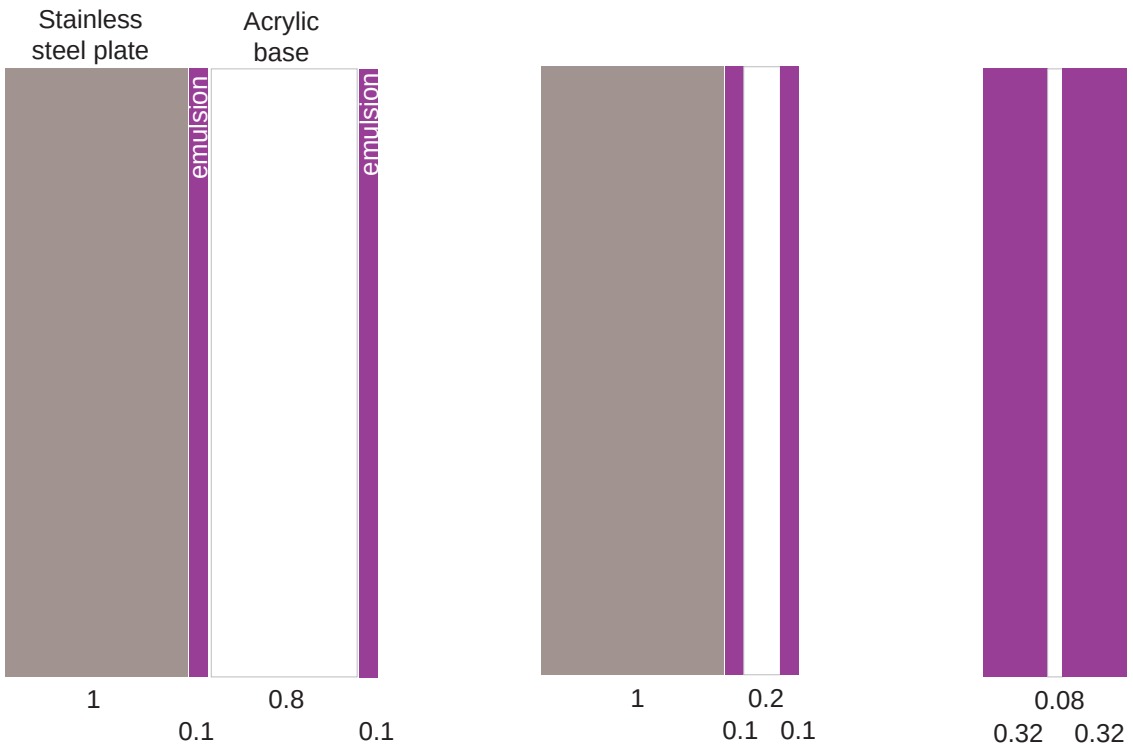
AgBr suspended in a gel is coated on plastic sheets.

- Fuji ET7C
- Grain size 0.7±0.2μm
- 29±2 grains per 100μm for m.i. track
- *Information capacity* (i.e. 50x50x6 cm^3) :

  $1x10^5$ tracks/cm^2 @ 3000 grains/cm ⇒

  10^{12} grains ⇒ ~ Terabytes of data

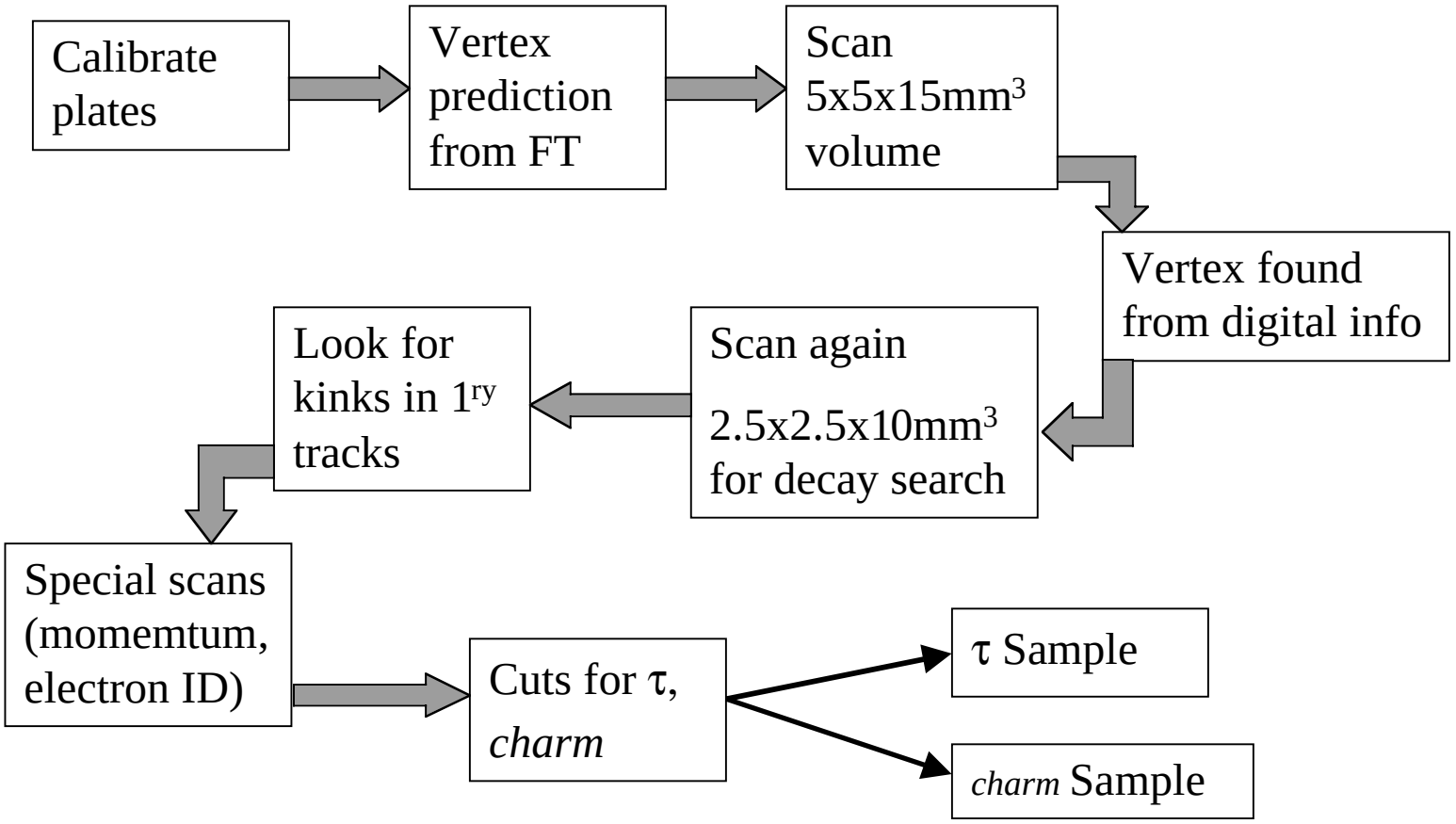
Target Designs



"ECC 800" "ECC 200" "Bulk"

- 3 target types
- Bulk 95% emulsion
- ECC 5% emulsion
- ECC for OPERA

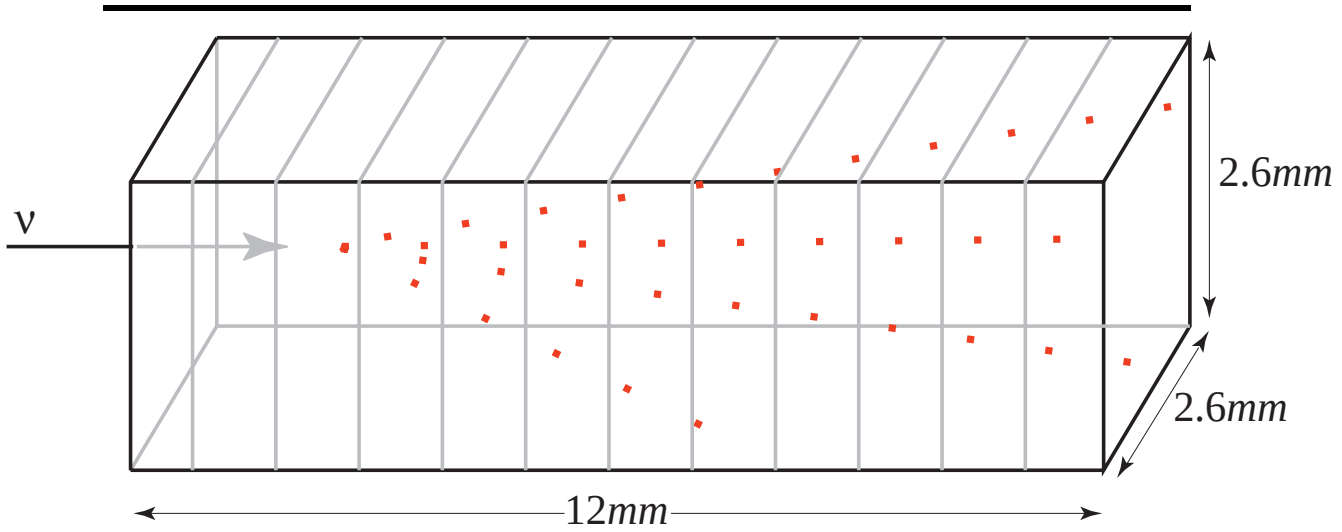
Digital Emulsion Analysis



Digital Emulsion Analysis:
Scanning Stations

Emulsion Scan Volume

Decay Search

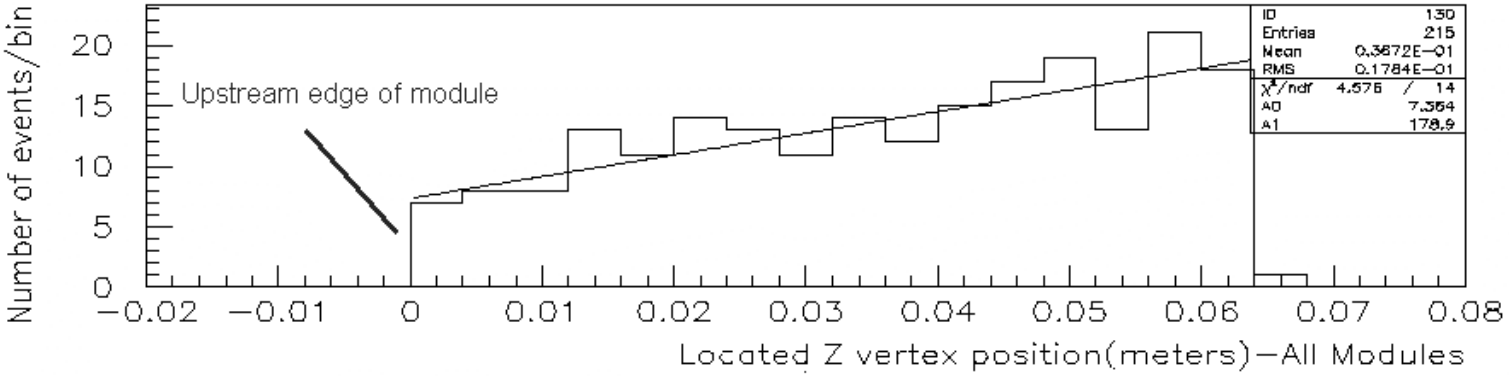


- Emulsion data digitized, stored on disk
- Vertex, decay search similar to electronic detectors

Emulsion Scanning Efficiency: 1ry Location

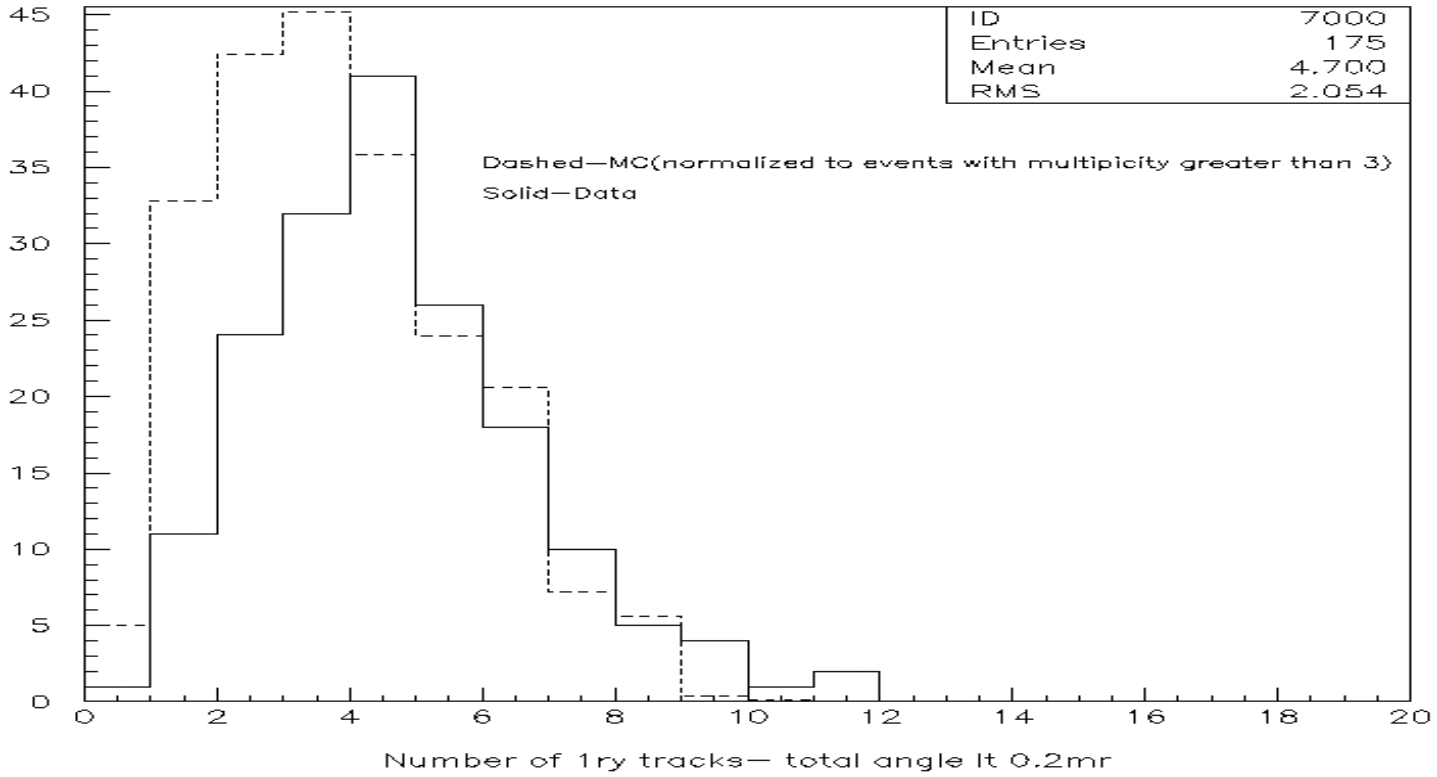
- Location efficiency factored into two independent parts:

  → Expect uniform(flat) z-vertex distribution within module. But … Easier to find interactions on downstream edge of module:



Emulsion Scanning Efficiency: 1ry Location (*cont.*)

→ Higher multiplicity events are easier to find. Some bias against low multiplicity interactions.



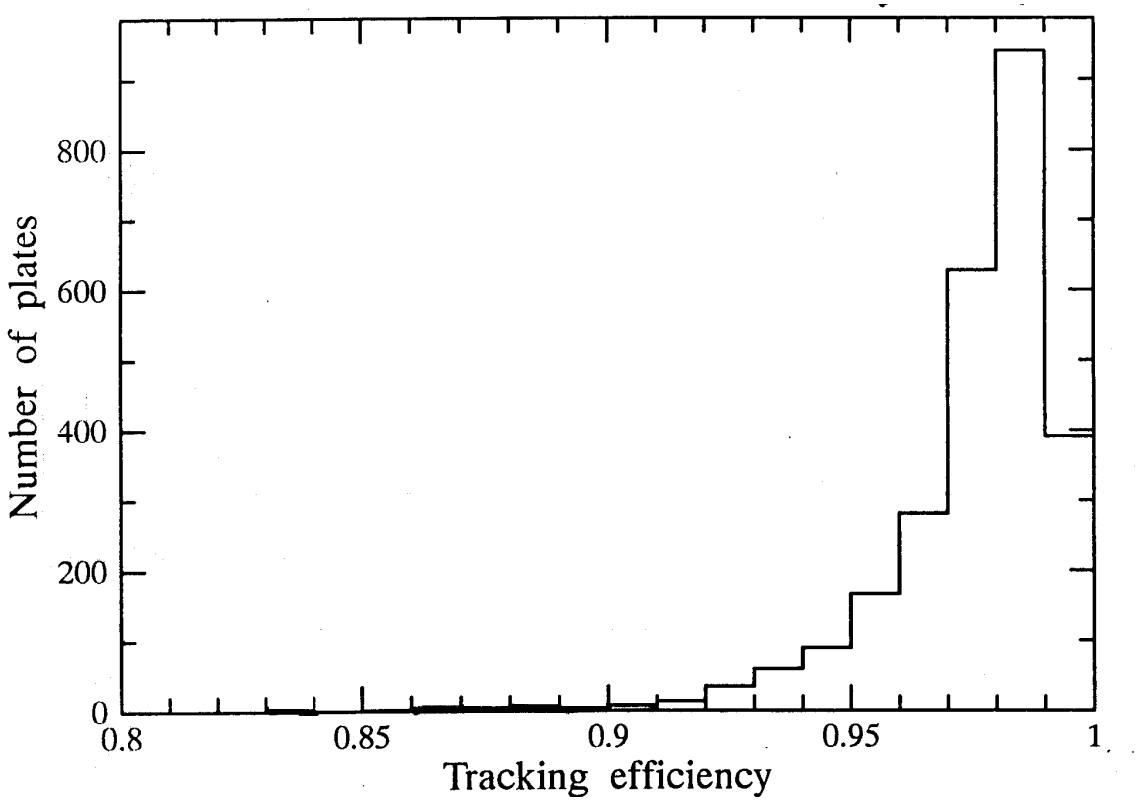
Emulsion Scanning Efficiency: 1^{ry} Location

- From the shape of located z-vertex distribution and comparing the expected 1^{ry} charged track multiplicity to the data one can extract the following 1^{ry} location efficiencies for different ν interaction types*:

ν interaction type	*Location Efficiency*
ν_{cc} (e,μ's only)	52 $\pm$10%
ν_{nc} (all types)	46 $\pm$9%
ν_{cc} + Charm	52 $\pm$10%
ν_τ cc	55 $\pm$11%

*Overall location efficiency from data: (located/attempted) = 52$\pm$6%

Emulsion Performance: Plate Efficiency

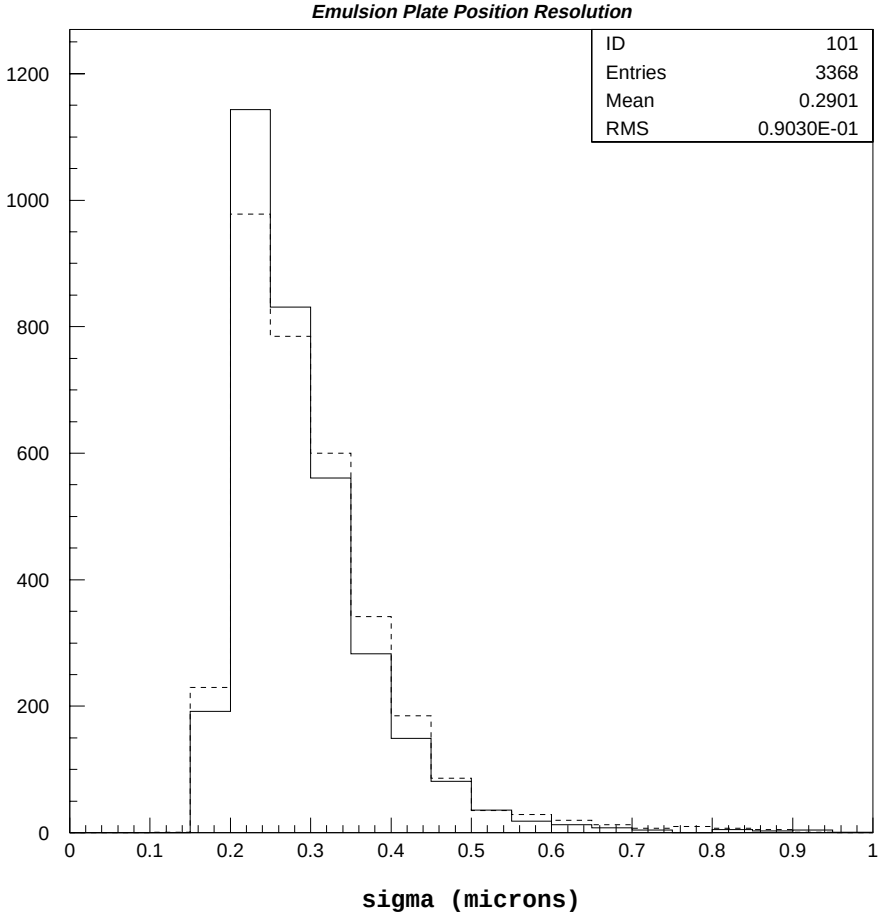


Tracking Efficiency for 2632 plates

Track θ < 0.1 rad

Only 24 plates with connection efficiency below 90%

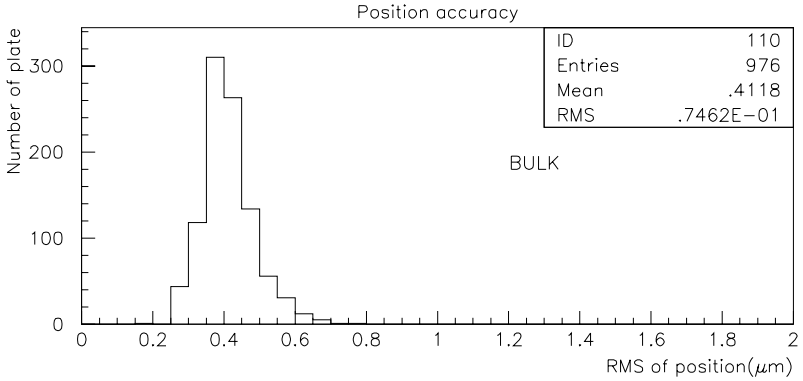
Emulsion Performance: Spatial Resolution

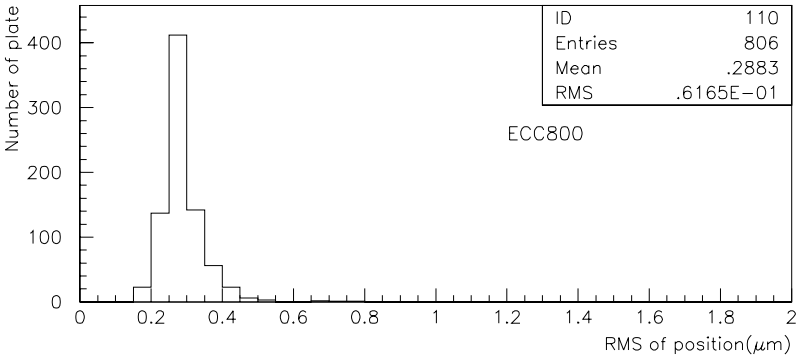


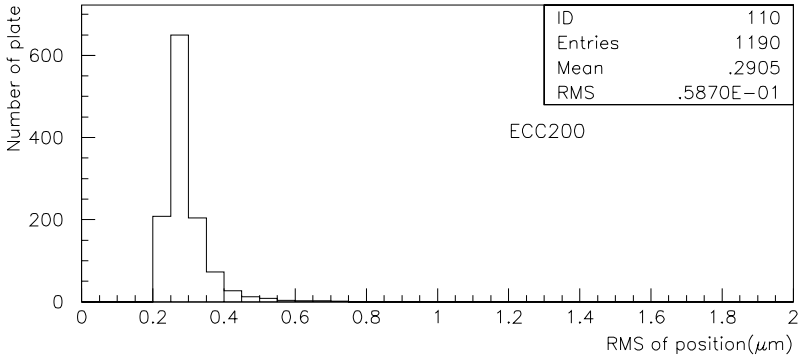
The emulsion track residuals

Average : 0.29 μm

Emulsion Performance: Spatial Resolution



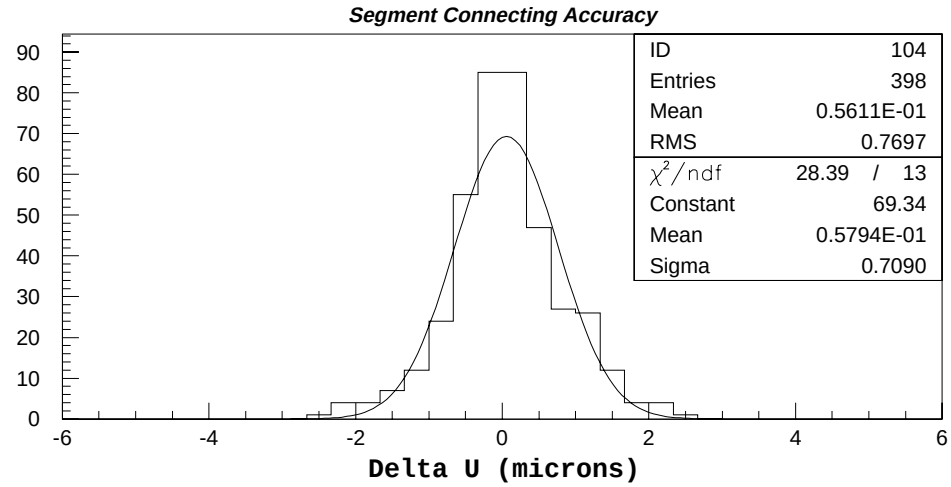


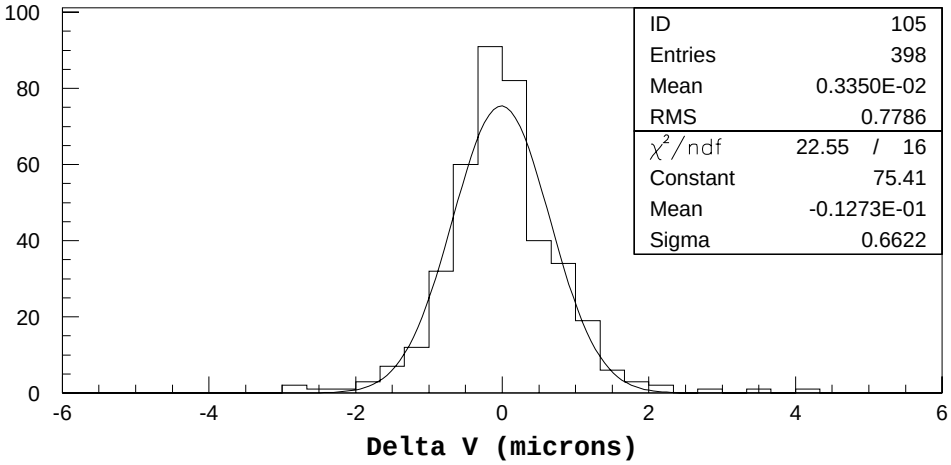


Emulsion data calibrated to 0.3 μ*m* in transverse coordinates (0.4 μ*m* for bulk emulsion)

Typical vertex precision (C5) 0.5 μ*m* transverse, and 15 μ*m* along beam

Emulsion Performance: Vertex Precision

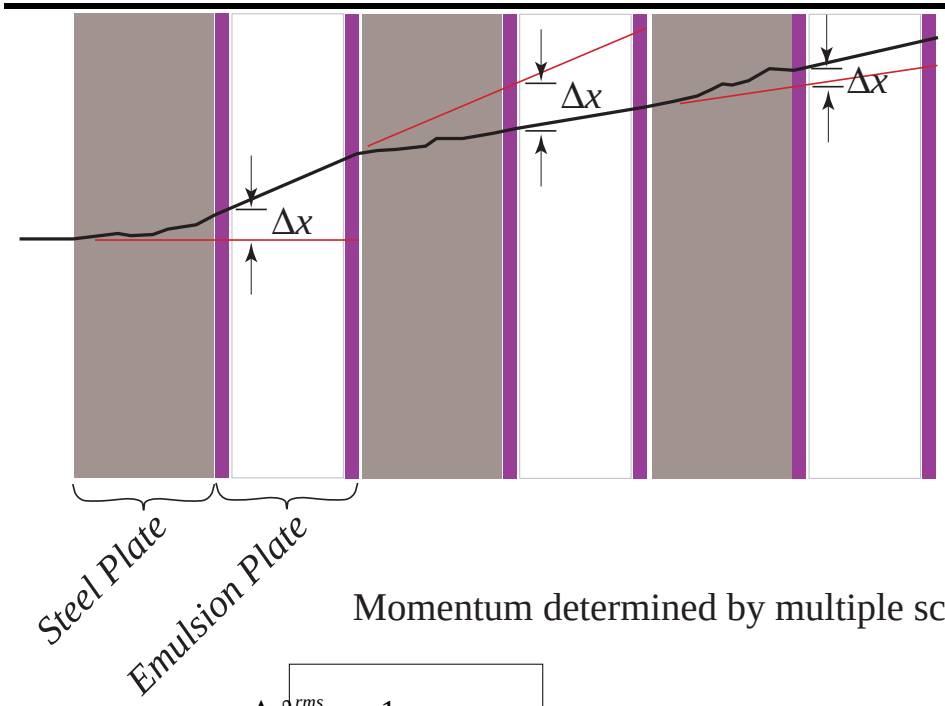




Distance of approach of emulsion tracks to the primary vertex with $\theta < 0.1$ rad

rms = 0.8 μm

Momentum Measurement using Multiple Scattering in Emulsion Targets

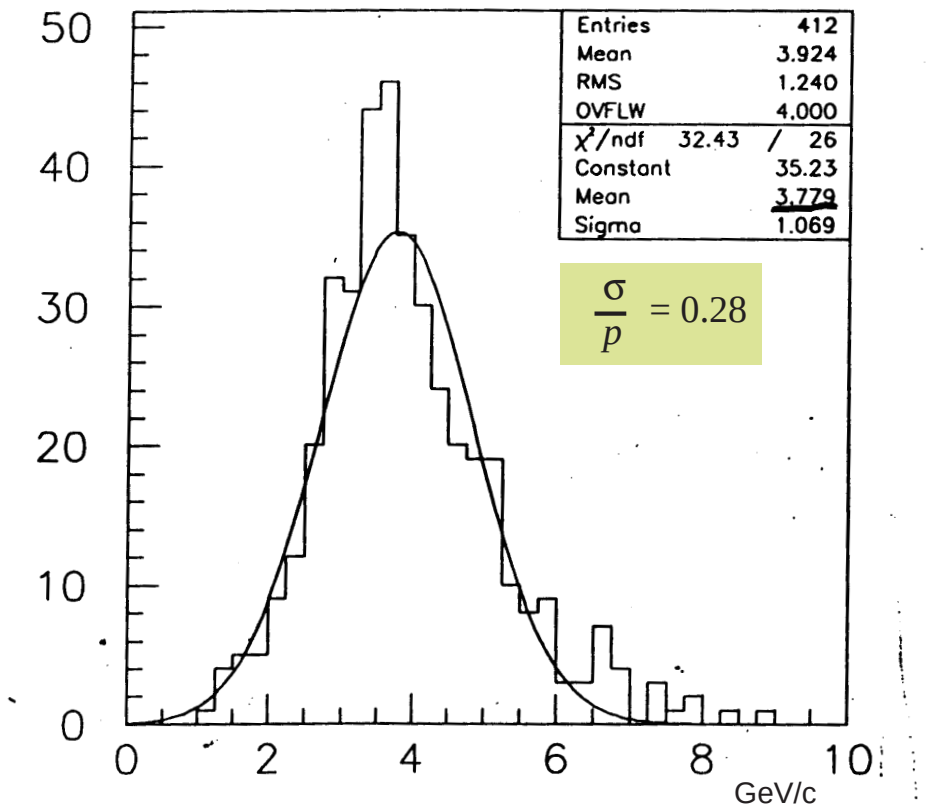


Momentum determined by multiple scattering:

$$\frac{\Delta\vartheta^{rms}}{\vartheta^{rms}} \propto \frac{1}{\sqrt{n}}$$ n : number of measurements

For example: 10 GeV/c has *rms* deflection of 0.3μm

Momentum from Scattering: Test Beam Results

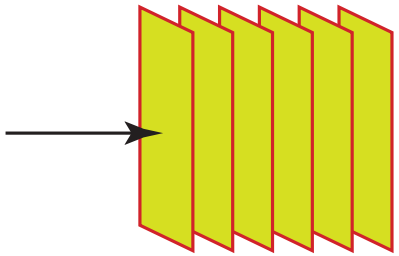


Momentum Measured using Multiple Scattering

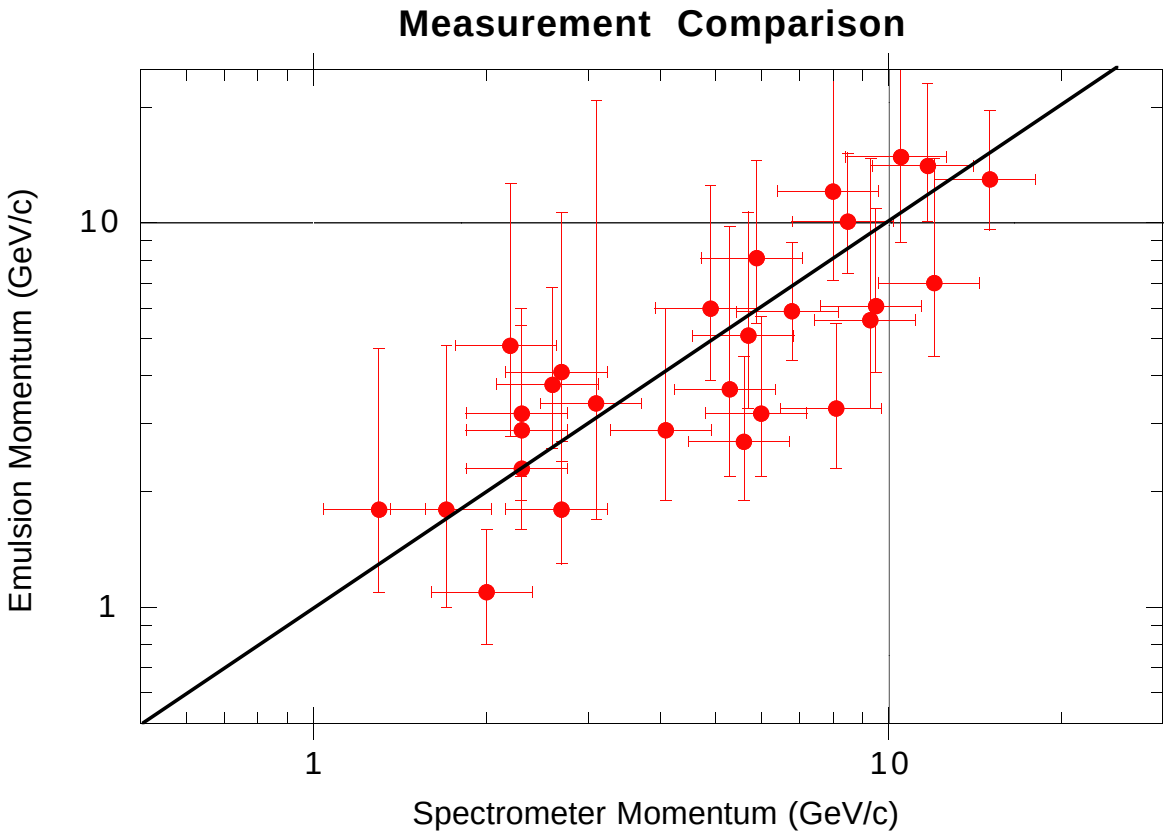
Beam Test

4 GeV/c π^-

Stack of 29 bulk plates

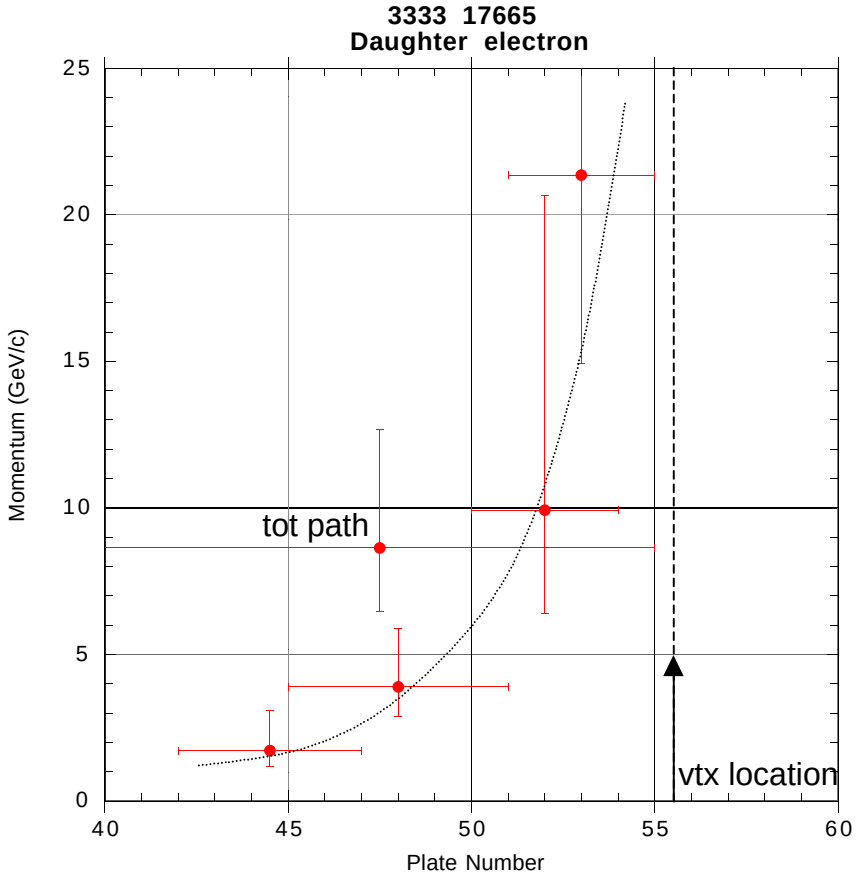


Momentum from Multiple Scattering: Calibration in DONUT



rms = 35%

Momentum from Multiple Scattering: Electron Energy Loss



Electron ID / energy loss

Scattering method applied to $e^{\pm}$ is usually a lower limit to p_e

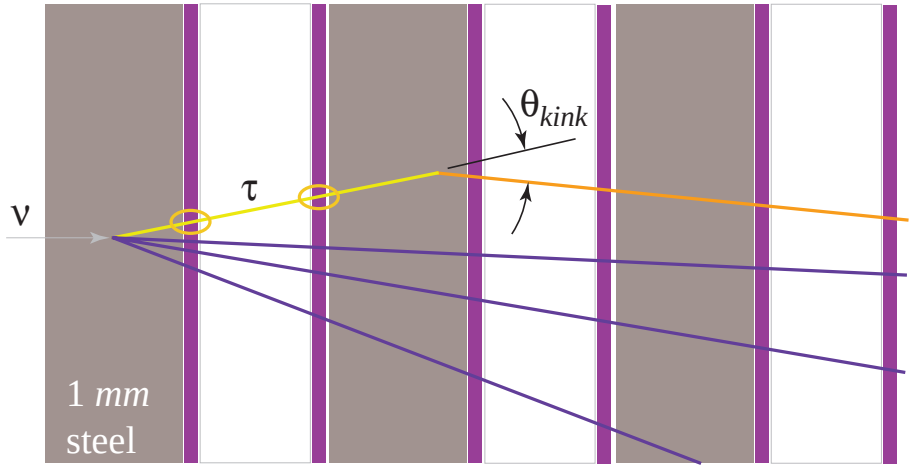
Intermission

- The achieved emulsion performance exceeds our initial expectations
- Located interactions have been verified in the SFT
- The 203 data set is fully calibrated
- We can measure momenta with emulsion data, reliably to 20 GeV/c
    - *Important for decay search*

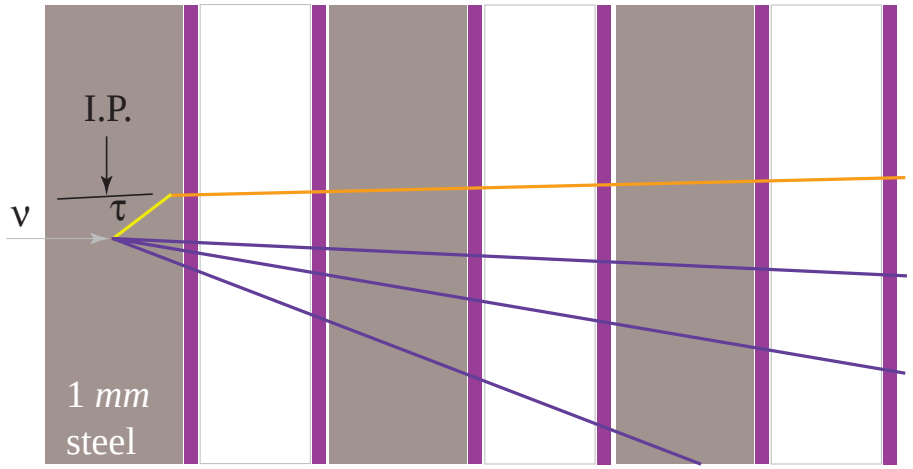
Decay Search

- Strategies: "Long" kinks
  "Short" kinks
- Cuts on kink data for τ search
- Decay search efficiency estimate

C1 Decay Search

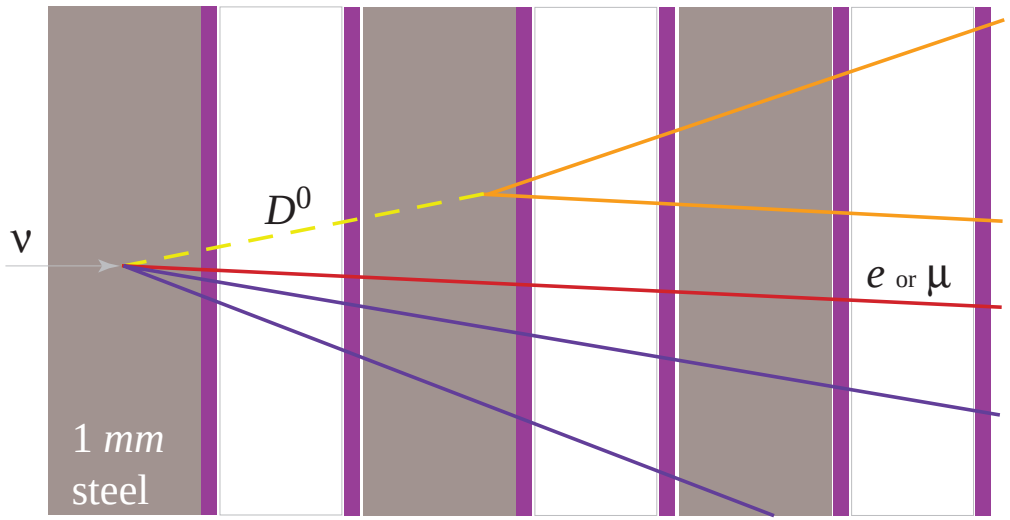


1. *Long Decays*
   - parent measured
   - kink resolved
   - $\tau \Rightarrow$ no 1^{ry} *lepton*
   - ~75%



2. *Short Decays*
   - IP wrt 1^{ry} vertex
   - only daughter meas.
   - daughter seen in spect.
   - ~25%

Neutral Decay Search



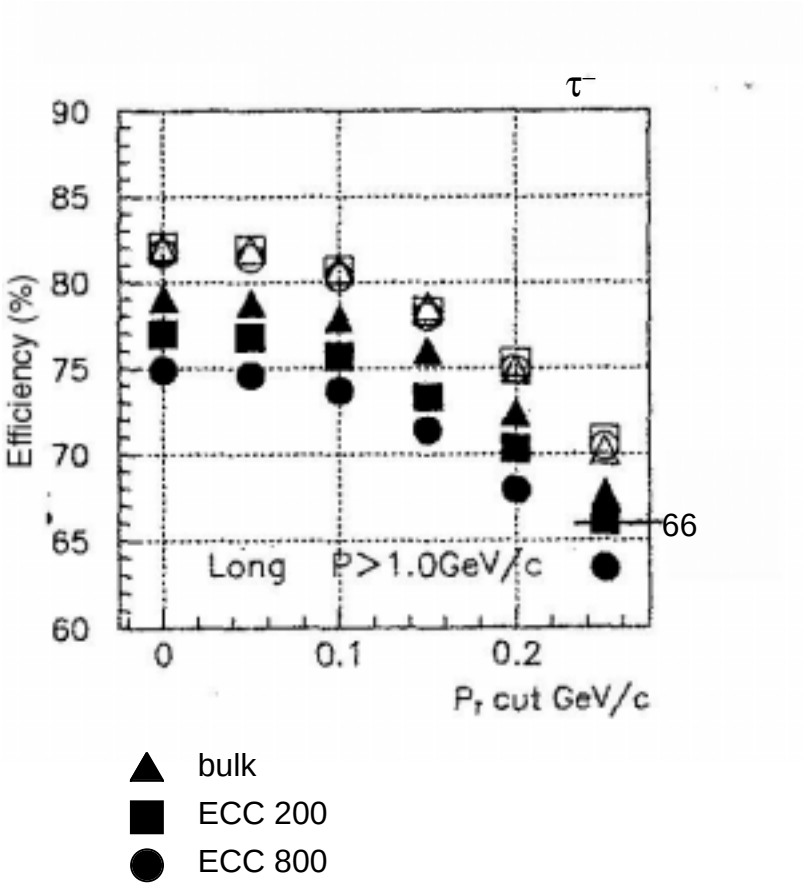
3. *Neutral* search
   - *charm* only
   - daughters in spect.

Decay Search: Kink Selection

Cut	kinks	$\%\tau$ remaining*
none	7642	100
0.01 < kink angle < 0.250	450	78
Parent angle < 0.20 rad	280	90
IP (parent) < 5μm	142	>99
IP (@ kink) < 5μm	65	>99
Flight length < 5mm	42	78
C1 (kink)	42	86
"Long" decay		76
Total		72

*not cumulative

Decay Search: Kink Finding Efficiency



Kink finding efficiency as a function of p_T

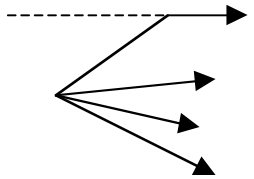
for $p_T > 250$ MeV/c :

$\varepsilon_{kink}(\tau) = 65\%$

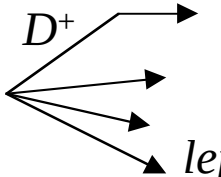
$\varepsilon_{kink}(D^{\pm}) = 56\%$

Kinks: Classification

- Randomly associated tracks
  - e.g. Primary track + stale muon track

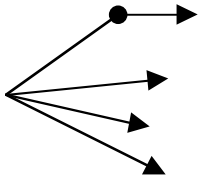


- *Charm* background

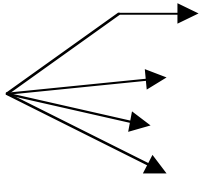


lepton : not recognized

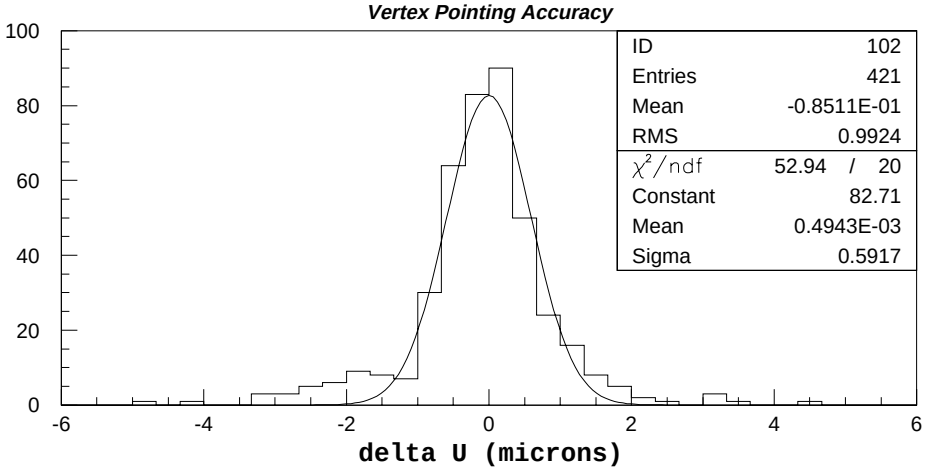
- Interactions (scattering)

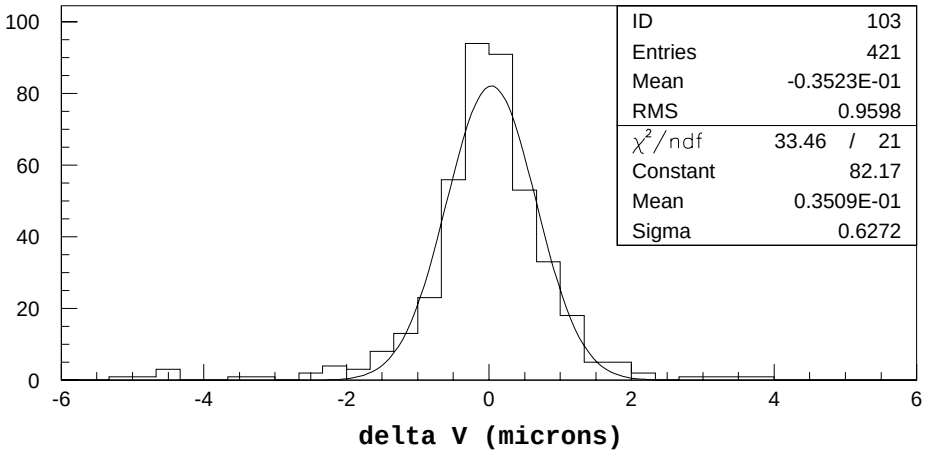


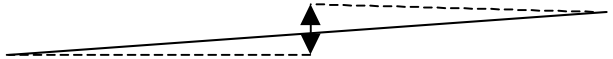
- Tau signal



Backgrounds: Random Association



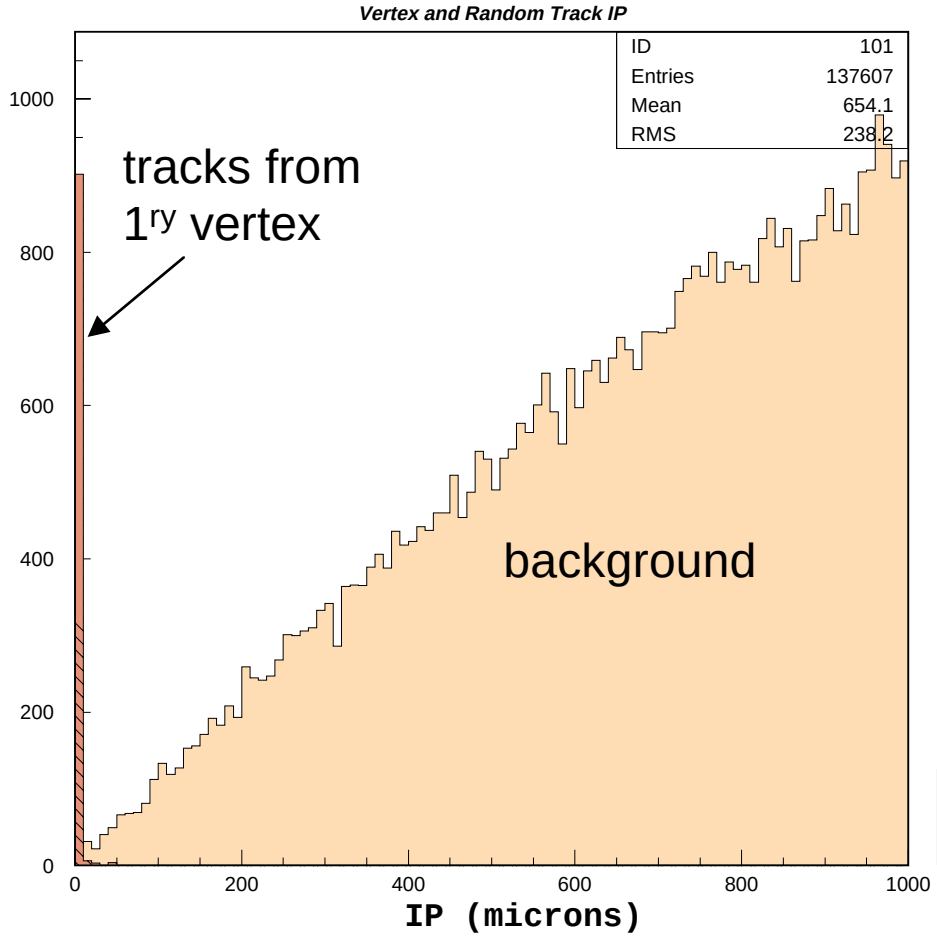




Procedure: "Break" a track from the primary into two pieces, then find the distance between the two, refit tracks

rms = 1 μm

Backgrounds: Random Association



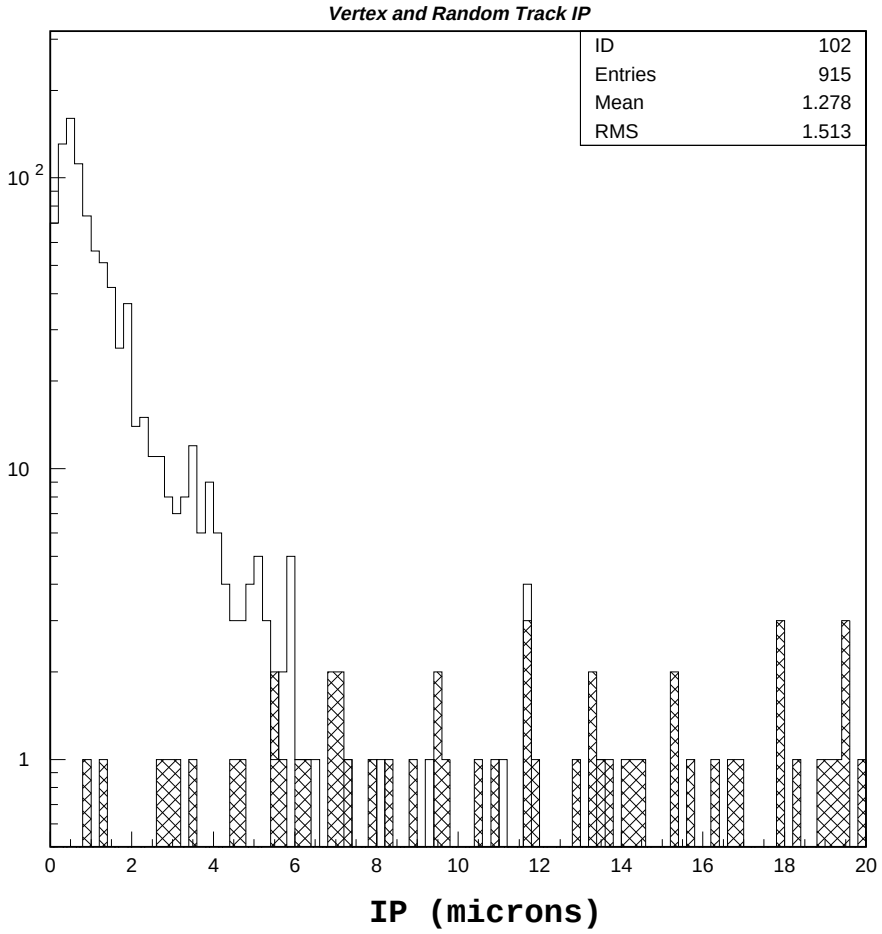
For each event, *all* tracks starting within 1 plate of the vertex are shown

The shape is characteristic of uncorrelated, uniform distribution:

$\Rightarrow$ 80 tracks/mm^2/event

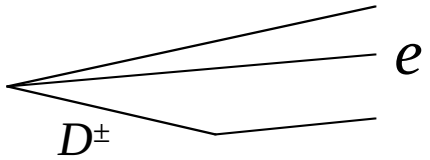
Est. random kinks < 10^{-3}

Backgrounds: Random Association



Same set of track as in previous slide, but showing only IP < 20 μm

Only 6 tracks within 5μm



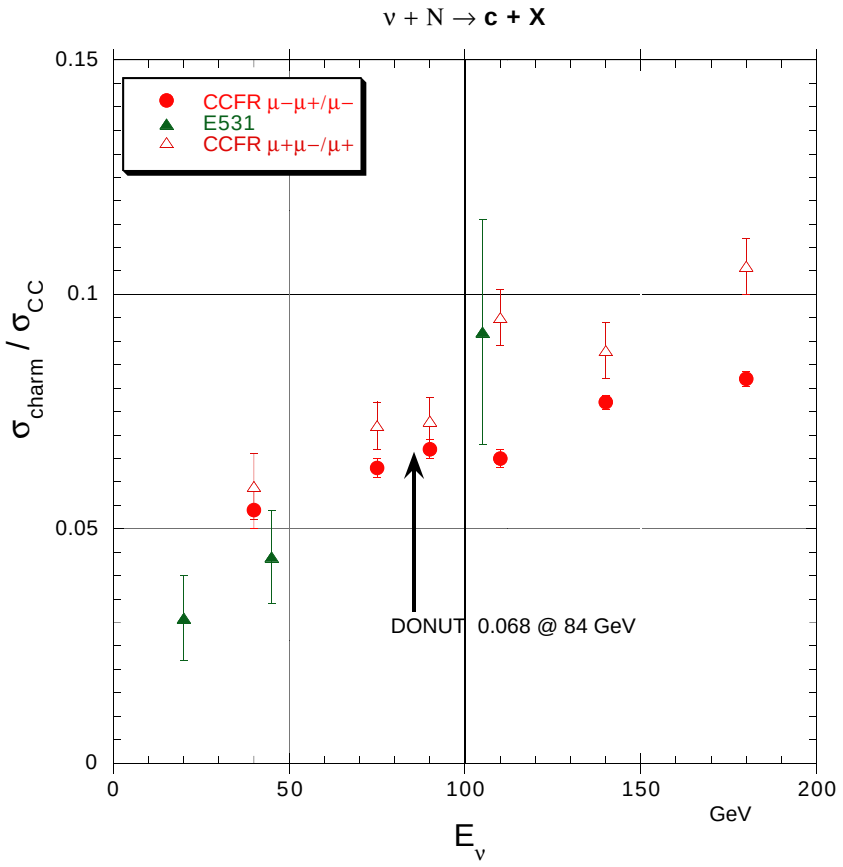
Background : *charm* Production

1. assume $\nu_\mu \sim \nu_e$	168±18	no. CC int.
2. *charm* production	0.081±0.008	13.6±1.3
3. charged charm	0.47±0.05	6.4±0.9
4. "Long" decay & < 5mm	0.66±0.06	4.2±0.7
5. kink detection effic.	0.56±0.06	2.4±0.5
6. *charm* → kink (C1)	0.38±0.02	
$\Pi_{1..6}$	0.9±0.2 events	[1.5 (inflate all 1σ)]

Expect 2.4 charged *charm* decays : found 2

Expect 0.9 *charm* kink decays : found 1

charm Production

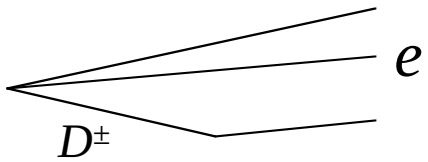


Neutrino-produced charm data

CCFR
E531

~~For DONUT charm total avg: 0.068±0.004~~

Update:
NuTeV preliminary results: 0.078±0.007



Background: *charm* summary

We estimated 0.9±0.2 *charm* events with *kink* :

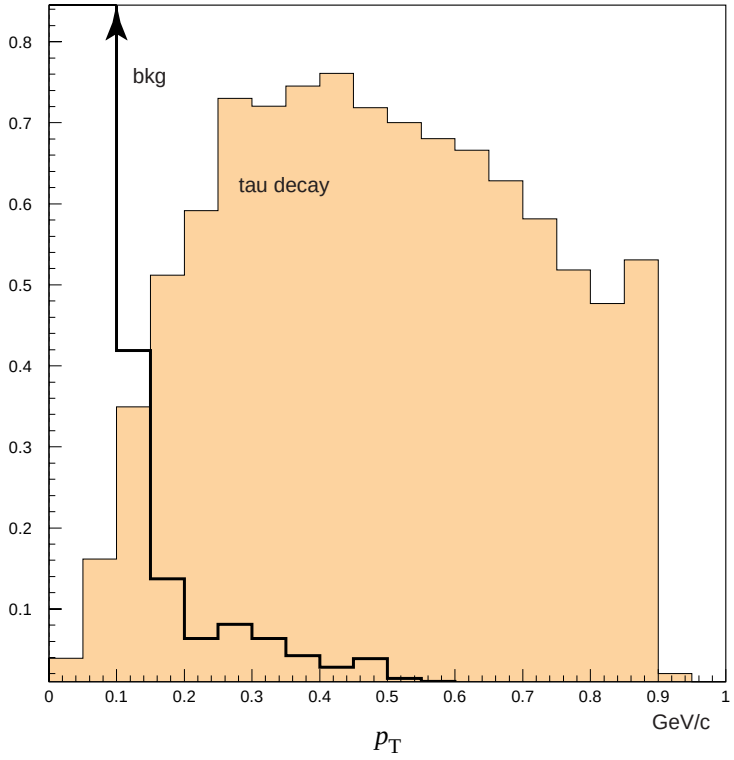
This is a background to τ *iff* the *lepton* is not identified as such

- μ ID prop tubes cover 82% of acceptance × 96% eff. = 79%
- *e* ID require >$2X_0$ for emulsion tag or >$3X_0$ FT : 75%

$\therefore$ *Total charm background* : 0.23×0.9 = 0.21±0.04 events

τ Background : *Interactions*

"NC interactions" + hadron scatter = τ background



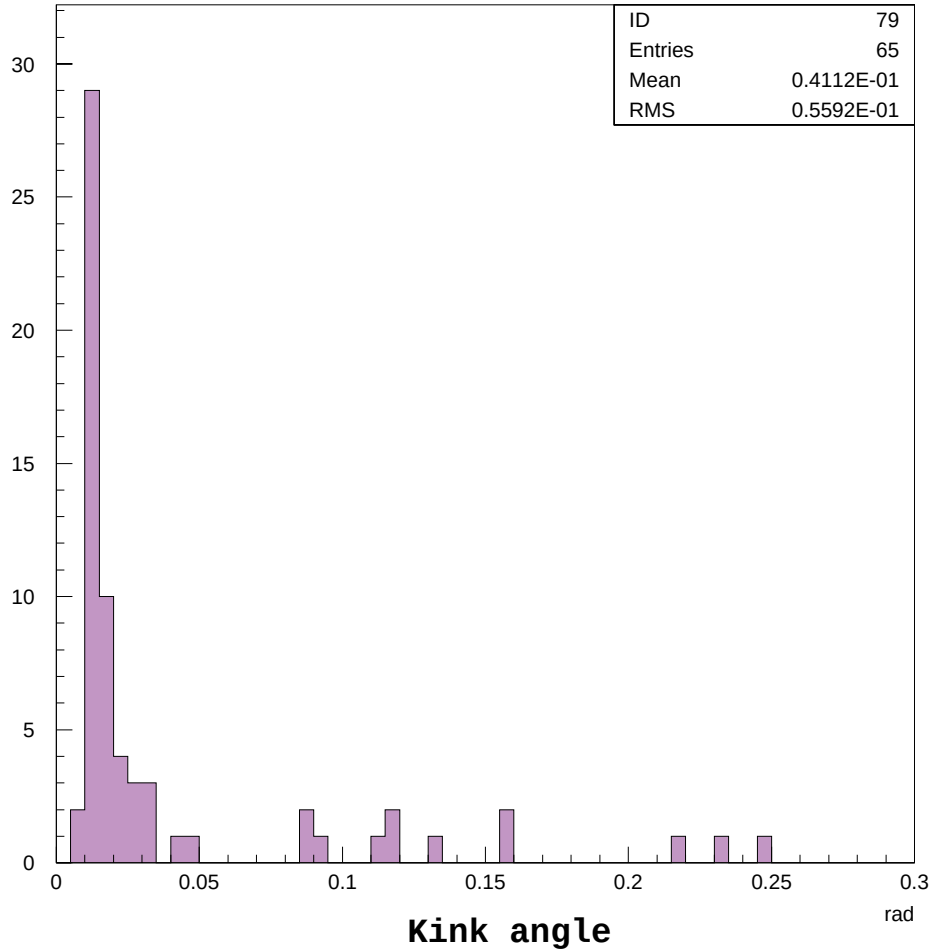
- Rapidly decreasing with p_T
- Depends on total path length
- *Short* decays is separate analysis

Estimated background using GEANT calculation :

0.20±0.06 events

for p_T > 250 MeV/c

Background: Interactions Distribution of Kinks



All kinks from analysis of the 203 set with:

$0.01 < \theta(\text{kink}) < 0.25$;

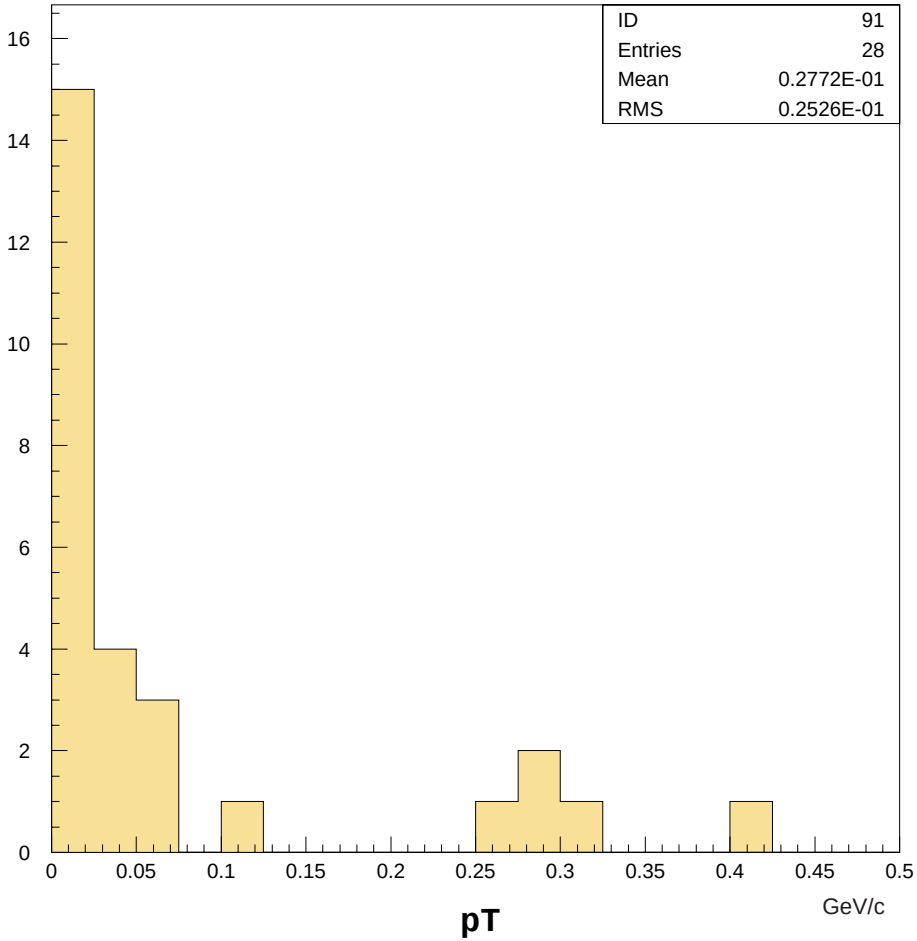
$\theta(\text{parent}) < 0.20$;

IP(parent) < 5 μm;

IP(@kink) < 5 μm

65 tracks out of 654

Background: Interactions
Distribution of Kinks

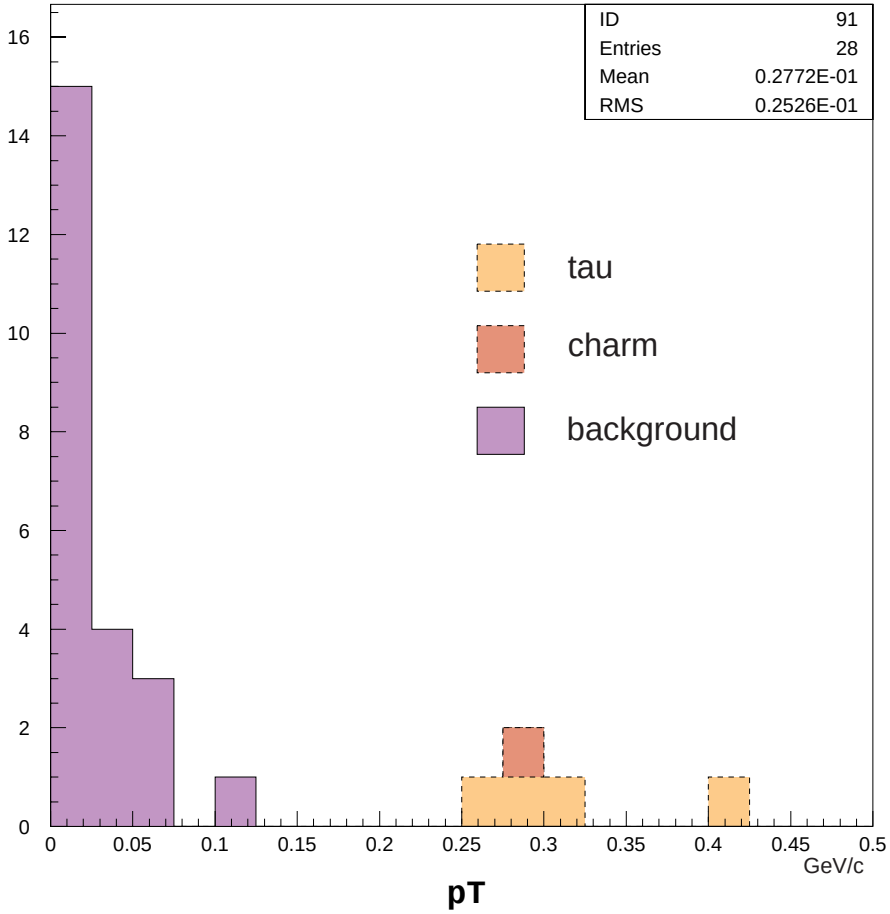


Kinks for which p_T is computed using scattering

It does not include all kinks from kink list

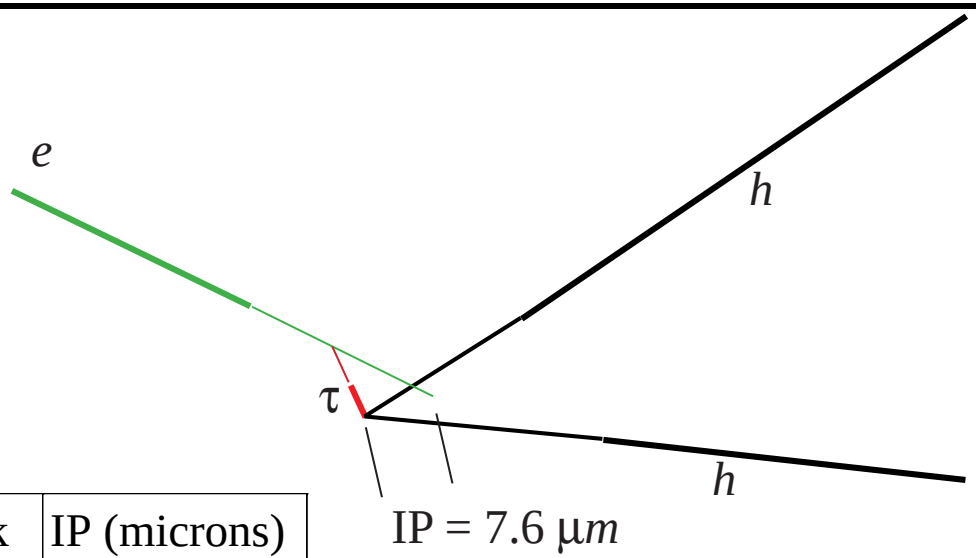
Recall: only tracks in "NC-like" events are part of τ background (~39%)

Background+Signal: Interactions Distribution of Kinks



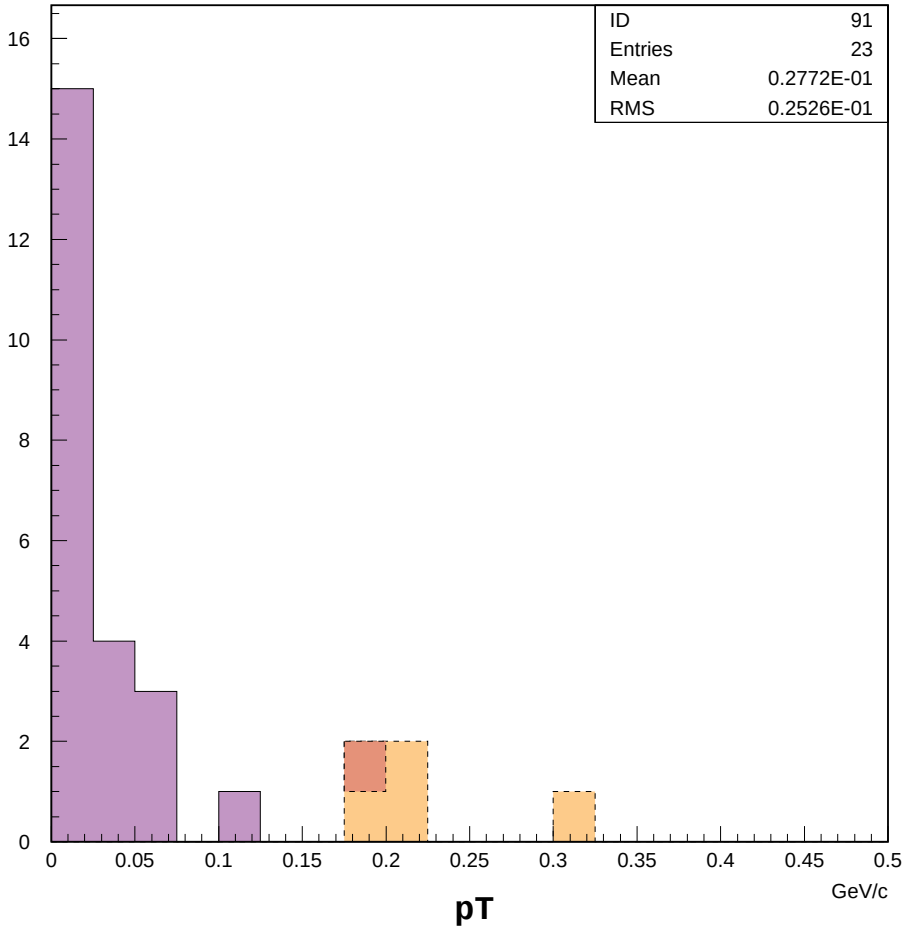
Same plot as previous slide, but *color enhanced* !

3333 17665
Magnified



Track	IP (microns)
4101	7.56
4107	0.11
4094	0.07
4033	0.91

Background+Signal: Interactions Distribution of Kinks



What if *each* signal event is a +1 σ fluctuation ?

Lower momentum for all tau events by 1 σ

Signal still separated!

Summary: τ candidates

from 203 set

- 4 events from *Long* decay search;

expect (203)(0.048)(0.86)(0.76)(0.65) = 4.1±1.4

τ frac C1 decay *Long* *kink eff*

Background Analysis:

Charm : 0.21±0.04 events

Hadronic interactions : 0.20±0.06 events

Sum Background: 0.41±0.15 events

Fluctuation bkg → signal : Poisson prob. 8×10^{-4}

Next steps

- "Short" Decay Analysis to be completed
- Complete detailed characterization of data set
- The data set *can* be doubled ...

In Conclusion

- "Long" Decay Search kink list only 65 events (after cuts)
- Randomly assoc. kinks $<10^{-3}$ for entire 203 event set
- *charm* background for τ calculated at 0.21 ± 0.04 events
- Interaction background calc. at 0.20 ± 0.06 events ($p_T > 250$)
  - Kink data supports MC calc.
- Signal events far from kink background in p_T

$\Rightarrow$ We conclude that these events are the evidence for observing the process:

$$\nu_\tau + N \rightarrow \tau + X$$

Acknowledgements

DONUT would like to thank the Fermilab support staff for helping make our little experiment a big success